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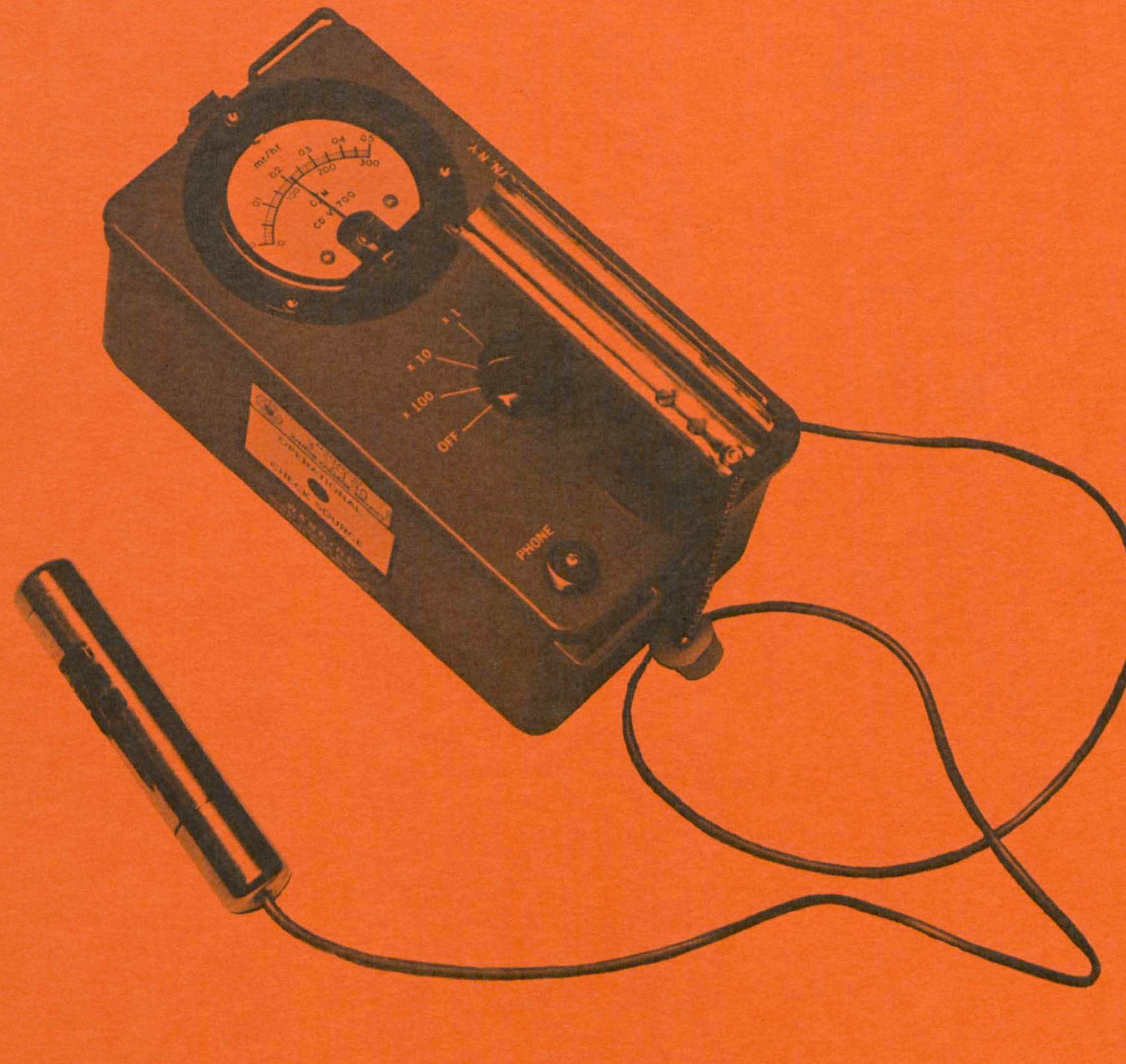

THE GEIGER COUNTER

Radioactivity and Nuclear Physics.

THE GEIGER COUNTER

A Module on Radioactivity and Nuclear Physics

ORAU

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MCGRAW-HILL BOOK COMPANY

NEW YORK
ST. LOUIS
DALLAS
SAN FRANCISCO
MONTREAL
TORONTO

The Physics of Technology modules were conceptualized, edited and printed copy produced by the staff at Indiana State University at Terre Haute, Indiana. The staff involved in the project included:

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This module was written and tested at the Oak Ridge Associated Universities and with funding of the [illegible] Foundation.

The authors wish to express their appreciation for the help of many people in bringing this module to final form. The criticisms of various reviewers and the cooperation of field-test teachers have been most helpful. Several members of the staff of Oak Ridge Associated Universities also deserve special recognition for their contributions. They are: Lawrence [illegible], John F. Vago, John Amend, [illegible], and Jo Templeton.

The Geiger Counter

ISBN 0-07-001733-X

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THE GEIGER COUNTER

PREFACE

This module studies the Geiger counter and those properties of matter that can be explored by using the Geiger counter. The study deals with the atomic nucleus and the kinds of radiation given off by atoms that are radioactive. Also included is a study of the electrical circuit of the Geiger counter and the processes that take place as radiation is detected.

The module is written with the idea that you can proceed through it with minimum help from your instructor. The laboratory instructions, questions, and problems are scattered through the text at appropriate points.

Some questions are meant to stimulate further thought. They cannot be answered merely by quoting or paraphrasing the text. You should be able to answer them, however, by a combination of an understanding of the text material, some common sense, and perhaps some previous knowledge of science. The ability to give clear answers to such questions is an important goal of a scientific study of any subject.

We hope that you enjoy the module.

PREREQUISITES

Before you start on this module, you should understand a few ideas about energy, work, and electric charge. Specifically, you should be familiar with:

1. Kinetic energy ($\frac{1}{2}\ mv^2$), and how to find it.
2. How to find changes in gravitational potential energy (*Wh*).
3. Conservation of energy.
4. How to find the work done when a force moves an object in a straight line (*Fd*).
5. The relationship between work and energy.
6. Electric current.
7. Electrical potential difference (voltage).
8. The attraction and repulsion of electric charges.
9. Potential energy of an electric charge in an electric field.
10. The procedure for operating an oscilloscope.

If you are not already familiar with these ideas, you may learn about them from other Physics of Technology modules, such as *The Cathode Ray Tube,* or from other sources. The following prerequisites test will tell you where you stand. If you can answer all of the questions, you are certainly ready to start on this module. If you have trouble with some of them, get some help from your teacher or another student.

PREREQUISITES TEST

(Note: There is more than one correct answer to some questions.)

1. Which of the following possesses kinetic energy?
   a. A bird flying through the air.
   b. A tennis ball moving with a speed of 50 ft/s.
   c. A stretched spring (motionless).
   d. The moon.
   e. The flywheel in an automobile engine (engine running).

2. If a car which is moving at a constant speed of fifteen mph accelerates to thirty mph, its kinetic energy
   a. does not change.
   b. becomes twice as large as before.
   c. becomes four times as large as before.
   d. becomes half as large as before.

3. A Toyota and a Buick which has twice the mass of the Toyota are both traveling at twenty miles per hour. The kinetic energy of the Buick is
   a. the same as that of the Toyota.
   b. twice as large as that of the Toyota.
   c. four times as large as that of the Toyota.
   d. half as large as that of the Toyota.

4. Which of the following possess potential energy?
   a. A bird flying through the air.
   b. A stretched spring (motionless).
   c. A storage battery.
   d. A pole vaulter at the top of his vault.

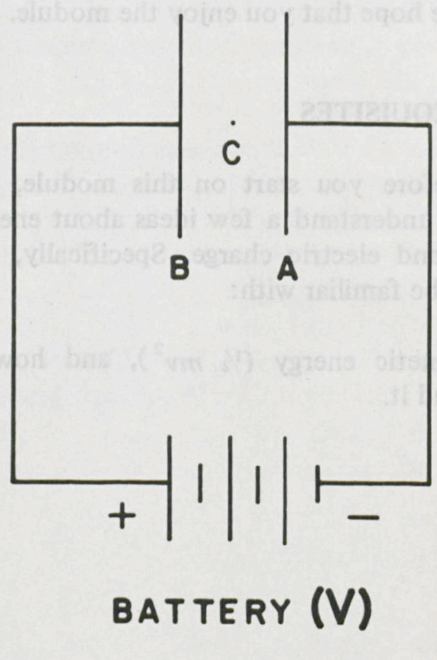
5. The amount of work necessary to lift a box which weighs W to a height h is
   a. Wh.
   b. W/h.
   c. Whg.
   d. none of the above.

6. If a box is raised to a different level, the work which was done on the box is changed into
   a. heat.
   b. kinetic energy of the box.
   c. potential energy of the box.

7. If a box is allowed to fall, which of the following statements are true?
   a. As the box falls, its potential energy is changed into kinetic energy.
   b. Just before the box hits the ground, its kinetic energy is greatest.
   c. While the box is in the air, the sum of the kinetic and potential energies of the box is constant.

Questions 8-12 refer to the circuit shown schematically. A and B indicate two flat sheets of metal which are parallel to each other. They are called *plates*. The combination of A and B is called a *parallel plate capacitor*.

8. The plate labeled A is
   a. negatively charged.
   b. positively charged.
   c. uncharged.



9. The potential difference between the capacitor plates is
   a. V.
   b. $V + IR$.
   c. $V - IR$.
   d. none of the above.

10. A negatively charged particle placed at point C will
   a. move toward plate A.
   b. move toward plate B.
   c. remain at point C.

11. A negatively charged particle placed between the plates of the capacitor will possess its greatest potential energy when it is near
   a. plate A.
   b. plate B.
   c. point C.

12. The amount of work done on a negatively charged particle which is placed near plate A and allowed to accelerate to plate B depends on
   a. the distance from A to B.
   b. the current in the circuit.
   c. the potential difference, V (voltage).

13. Indicate whether each of the following statements is true or false.
   a. Positive charges repel negative charges.
   b. The current in a circuit depends only on the amount of charge which flows through the circuit.
   c. The current in a circuit depends both on the amount of charge which moves through the circuit and on how fast the charge moves.

Answers appear in the Teacher's Guide.

GOALS

As you work through the module, you will learn:

1. What a Geiger counter is and how it is used to detect radioactivity.

2. How to describe the structure of atoms and simple molecules.

3. How to relate the structure of an atomic nucleus to the kind of radiation it emits, if any.

4. How to describe the three most common types of radioactivity.

5. What happens to an atom when it emits any of the three most common types of radiation.

6. How the observed radioactivity of a given sample can be expected to vary for repeated measurements.

7. How the radioactivity of a sample changes over a long period of time.

8. How the ability of radiation to penetrate matter depends on the mass and charge of the radiation.

9. How the interaction between a charged particle and the atoms in matter can produce a voltage change to indicate the presence of the charged particle.

10. How the type of radioactivity and other factors affect the voltage change produced in the electric circuit of a Geiger counter.

11. What happens when a Geiger counter is overloaded and how to correct for the overloading.

SECTION A

Some Introductory Observations with a Geiger Counter

INTRODUCTION

You know that Geiger counters exist and that they are used in prospecting for radioactive ores. You have probably also heard on TV programs the "clicking" sounds that supposedly come from Geiger counters. In this module you will learn how to operate a Geiger counter. You will also learn how it is made and the principles behind its operation. This will lead into a discussion of radioactivity and the structure of atoms.

Throughout the module we shall use the term *Geiger counter* to refer to devices that are sometimes designated by other terms: *Geiger Mueller counters, G-M counters, radiation counters, radiation detectors,* etc. The designation *Geiger-Mueller* refers to the inventors of the counter: Hans Geiger and W. Mueller.

Geiger counters are used to detect particular kinds of nuclear radiation. Section B of this module will be concerned with a description of these kinds of radiation and how they arise.

A Geiger counter consists of three basic units: *the detector, the electrical circuit,* and *the read-out unit* (see Figure 1). The detector is a *Geiger tube* (often called a *Geiger-Mueller tube* or *G-M tube*). A *count* is the response of the Geiger counter to a single bit of radiation entering the Geiger tube.

The read-out unit can be a meter (to indicate the rate at which the counter responds to radiation), a sound system (to give the clicks mentioned above), or a device for registering the number of counts.

Geiger counters which have any of the three kinds of read-out units are commercially available. Two of these are shown in Figure 2. The device shown in Figure 2a is large and complicated, but the one in Figure 2b is small and compact. The first has display lights to show the total number of counts in a given time and is called a Geiger-Mueller *counting system.* The second is called a Geiger-Mueller *survey meter.* The survey meter is designed to give a rough but quick indication of the rate of counting. The counting system is more expensive and more trouble to use, but it gives accurate counts.

The apparatus supplied with this module is a Geiger-Mueller counting system. As shown in Figure 3, it consists of two parts: (a) a scaler, consisting of an amplifier and a "decade counter," and (b) the Geiger tube and its power supply unit. In this module we shall use the term *Geiger counter* to refer to the Geiger tube and its power supply unit. The scaler is a device that can count and record the number of electric pulses that reach it. The scaler has read-out lights which indicate the total number of counts registered. Though most experiments will use both the Geiger counter and the scaler, it is the Geiger counter that we shall be studying in detail.

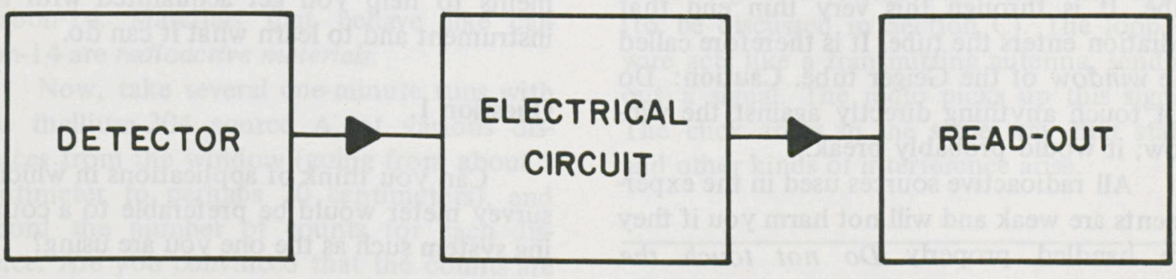


Figure 1. The units of a Geiger counter.

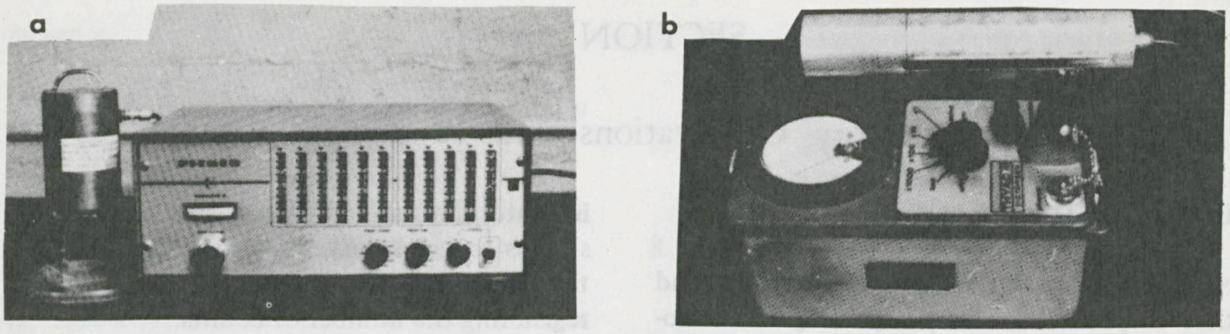


Figure 2. Commercial Geiger counters.

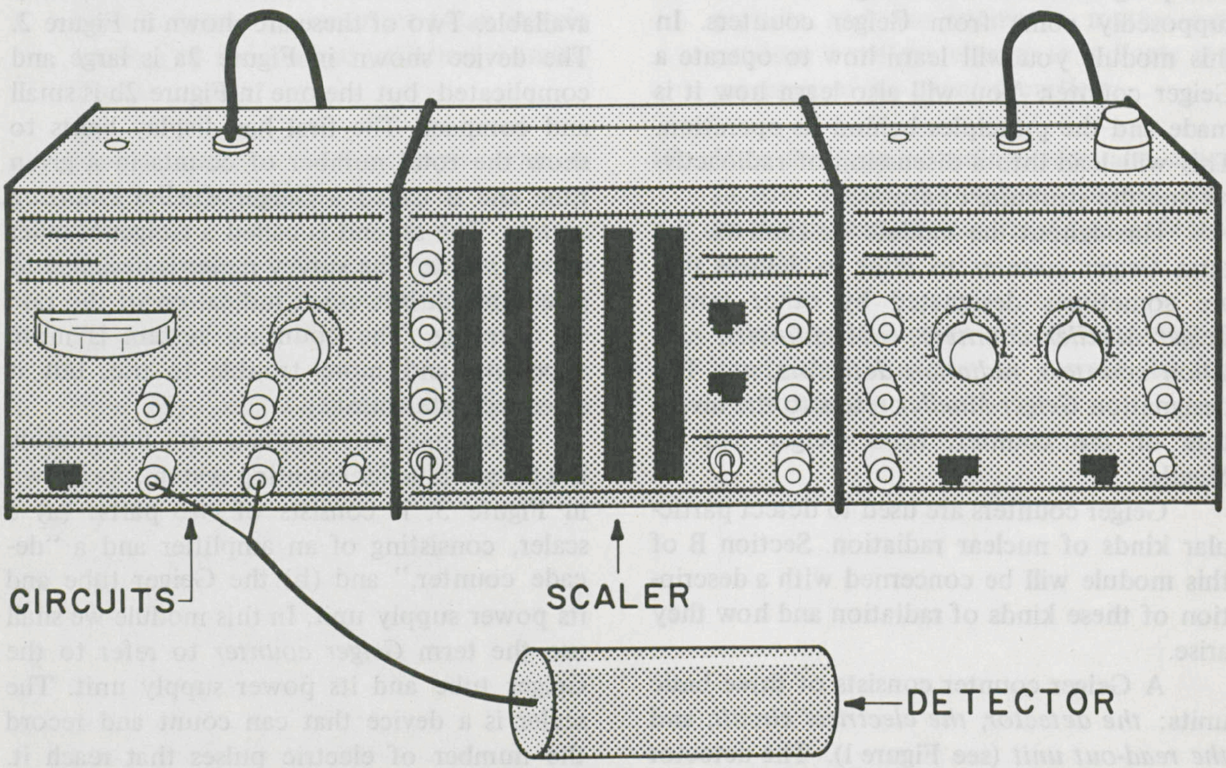


Figure 3. The student Geiger counter (with scaler).

The Geiger tube is enclosed in a protective envelope with a plastic end cover. Removal of the end cover exposes the end of the tube. It is through this very thin end that radiation enters the tube. It is therefore called the *window* of the Geiger tube. **Caution**: Do not touch anything directly against the window; it would probably break.

All radioactive sources used in the experiments are weak and will not harm you if they are handled properly. *Do not touch the sources themselves*; handle them with the holders in which they are mounted.

You are now ready to do a few experiments to help you get acquainted with the instrument and to learn what it can do.

Question 1.

Can you think of applications in which a survey meter would be preferable to a counting system such as the one you are using?

EXPERIMENT A-1a. An Introduction to Counting

Detailed operating instructions for the Geiger counter and scaler will be given by your instructor in special instruction sheets. Note, however, that the operating voltage of the Geiger counter has to be adjusted before the equipment is set in operation. Your instructor (or special instruction sheets) will specify the setting. You will also note that the scaler must be reset to zero before any counting is started. We shall use the word *run* to refer to going once through the set of procedures involved: resetting the scaler, turning it on to record counts, stopping it, and recording the result.

With the carbon-14 source placed close to the window, take a few runs of about one minute each. These runs will acquaint you with the controls.

After you are convinced that you can operate the controls, try a timed count, using a stopwatch. Do this until you are convinced that you know the various necessary operations involved in making a run.

Next, place the source about 3 centimeters from the window and take some one-minute counts with various absorbers between the source and the counter (your hand, thin paper, metal foil, etc.). What is the effect of these various absorbers?

The source used is a form of carbon known as carbon-14. Common carbon is carbon-12. See if a piece of carbon-12 causes counts. You might try other things (a pencil, a magnet, etc.). You should be able to conclude that not all materials cause counts. In fact, relatively few materials behave like carbon-14. Materials that behave like carbon-14 are *radioactive materials.*

Now, take several one-minute runs with the thallium-204 source A, at various distances from the window (going from about 1 centimeter to perhaps 20 centimeters), and record the number of counts for each distance. Are you convinced that the counts are due to the source?

To test your tentative conclusion, put the source very far away (at least 5 feet) and take a five-minute run. You probably will still observe counts. These are called *background counts,* which are due partly to radioactivity in the ground, building, and other surroundings, but which are due mostly to *cosmic radiation* coming from outer space.

Question 2.

Can you explain why the number of counts per minute decreased as the source was moved farther away?

Question 3.

In order to get the true effect of a source, background counts must be subtracted from the total count. Why is this?

EXPERIMENT A-1b. Making Counts Audible

Earlier we referred to the clicking sound from Geiger counters. Your Geiger counter can be used to produce such sounds in response to radiation.

Connect a piece of wire (at least 2 feet long) to the output terminals of the Geiger box. (Figure 4.) A small radio placed near the wire and turned on will give a click each time the counter responds to radiation. The radio should be tuned to a place between stations to make the clicks as clear as possible. Try the source in various positions to observe different counting rates.

The radio responds because the Geiger counter gives a voltage pulse* for each count (to be discussed in Section C). The loop of wire acts like a transmitting antenna, sending out a signal. The radio picks up this signal. The click arises in the same way that static and other kinds of interference arise.

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*A voltage pulse is a voltage change of short duration.

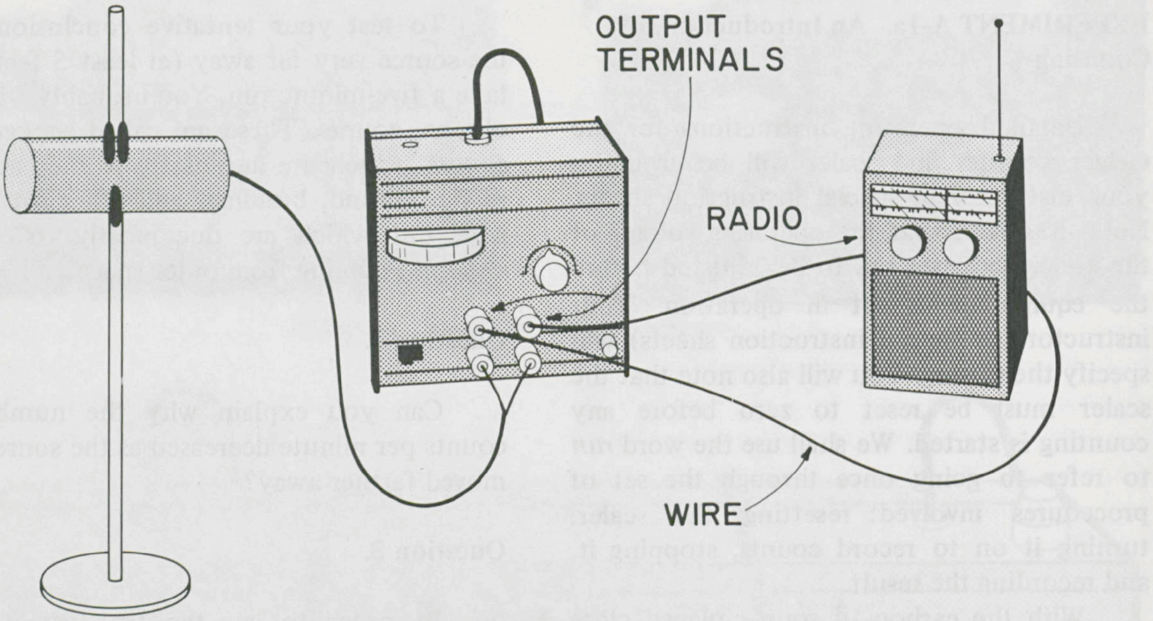

Figure 4. Making counts audible.

COUNTING AS A MEANS OF TAKING MEASUREMENTS

Measurements with which you are most familiar are probably length measurements (with a ruler or tape), meter readings (such as that of a speedometer, or gas gauge), temperature measurements (with a thermometer), weighings (with a balance or scale). You are now in a position to consider another kind of measurement: *counting*. In the discussion below, we will consider two questions about this kind of measurement: 1. Are counts repeatable? 2. Do counts "add up"?

EXPERIMENT A-2. Are Counts Repeatable?

With the carbon-14 source located in front of the window and far enough away to give between 150 and 200 counts in a minute, take 10 one-minute runs. Record the results in a data table. Do you always get the same number? Find the average number of counts in one minute.

You would expect that, if nothing changes in the experiment, the same result should be obtained for each run. But you observed a spread in the number of counts. If many runs are made, it is found that the number of counts obtained in each run is close to, but usually not equal to, the overall average. There should be about as many runs with the number of counts above the average as there are with counts below. This is not due to faulty apparatus or poor timing. The radioactivity itself is slightly different in different one-minute intervals. This difference gives rise to a kind of uncertainty: if 10 one-minute runs are made, it is still not possible to predict with complete certainty what the count will be for the eleventh run. However, this is called a *statistical uncertainty* because it is possible to predict statistically the approximate results of the next run.

How reliable then is a particular reading in such a measurement? This question cannot be given a quick answer. A detailed discussion will not be undertaken in this module. Only a few ideas will be presented.

Suppose you take a single run and want

to know how the results of repeated runs would compare with the first result. The *uncertainty* is a measure of the differences that might be expected between results of the first run and the various numbers obtained for many other runs. One way to get an *estimate* of the uncertainty is to use the square root of the number of counts measured in a run. The fact that this is a good estimate has been confirmed experimentally for counts from radioactive sources. In general for random events, it can be derived mathematically. Thus, if in a given run 100 counts are observed, the uncertainty is $\pm\sqrt{100}$, or ± 10. This means that repeated runs could be expected to give counts generally in the range 90 to 110. (However, any given run may well be under 90 or over 100.)

Note that in this case the uncertainty is 10% of the total. The *fractional uncertainty* is the uncertainty divided by the total:

$$\text{fractional uncertainty} = \frac{\text{uncertainty}}{\text{total number}}$$

If we use the letter N to represent the total number of counts, then the uncertainty is $\sqrt{N}$ and

$$\text{fractional uncertainty} = \frac{\sqrt{N}}{N}$$

$$= \frac{1}{\sqrt{N}}$$

For the example above, $N = 100$ and $\sqrt{N} = \sqrt{100} = 10$.

Thus,

$$\text{fractional uncertainty} = \frac{10}{100} = 0.1$$

or

$$\text{fractional uncertainty} = \frac{1}{\sqrt{100}} = 0.1$$

This is a 10% uncertainty.

It should now be clear that the uncertainty becomes less important as the number of observed counts increases. For example, for $N = 10{,}000$, $\sqrt{N} = 100$ and the fractional uncertainty is 0.01 (or 1%). Note, however, that the actual uncertainty is larger.

For your data, call the number of counts in the first run N_1. Find $\sqrt{N_1}$. Then find the fractional uncertainty. Do the other runs give results generally between $N_1 - \sqrt{N_1}$ and $N_1 + \sqrt{N_1}$?

Now compute the average for all 10 runs. Call this number N_{ave}. How does it compare with N_1? Calculate $\sqrt{N_{\text{ave}}}$. In general $\sqrt{N_{\text{ave}}}$ would be a better estimate of the spread in the 10 runs than would $\sqrt{N_1}$. From the theory of statistics, if the spread in the number of counts is truly random, one would expect about two-thirds of the counts to be within the range $N_{\text{ave}} - \sqrt{N_{\text{ave}}}$ to $N_{\text{ave}} + \sqrt{N_{\text{ave}}}$. Since we are dealing with probabilities, however, this is the prediction for what would happen for a large number of runs. For any given set of runs, it may not work this way at all. (For example, if you flip a coin a large number of times you can predict that the results will be divided about equally. Ten tails in a row could turn up, but not on the first try).

The *counting rate* is the number of counts divided by the time of counting. Thus, for your first run, where R is a rate:

$$R_1 = \frac{N_1}{t_1}$$

$$= \frac{100 \text{ counts}}{1 \text{ minute}} = 100 \text{ counts per minute}$$

For all of the runs added together, the *average counting rate* is

$$R_{\text{ave}} = \frac{N}{t}$$

where N is the total count and t is the total time for those counts. Then the uncertainty in the average rate is

$$\text{uncertainty in } R_{\text{ave}} = \frac{\sqrt{N}}{t}$$

The *fractional uncertainty* in the average counting rate is then:

$$\text{fractional uncertainty} = \frac{\text{uncertainty in } R_{\text{ave}}}{R_{\text{ave}}}$$

$$= \frac{\sqrt{N}/t}{N/t}$$

$$= \frac{\sqrt{N}}{N}$$

$$= \frac{1}{\sqrt{N}}$$

From these results you can conclude that greater accuracy (less fractional uncertainty) results from a measurement involving a large number of counts. But there will always be some uncertainty.

Question 4.

If you were measuring the length of a board, would a greater number of measurements imply greater accuracy? Why?

Problem 1.

How many counts would need to be taken if the fractional uncertainty is to be less than 2%?

Problem 2.

A student reported the following results for three similar runs. Is the spread of numbers reasonable?

	number of counts
Run #1	12,786
Run #2	10,462
Run #3	10,577

Problem 3.

If in Problem 2 each run was 10 minutes long, compute the average counting rate and the uncertainty in counting rate for the entire 30 minutes.

EXPERIMENT A-3. Do Counts "Add Up"?

Using the thallium-204 source #1, find a point some distance away from the Geiger counter window (Figure 5) such that you obtain a counting rate at least twice that of background. Mark that position and take a run long enough to obtain at least 1000 counts. Remove this source. Repeat this with the thallium-204 source #2, putting it in a different position. Now place both sources at their marked positions and make a combined run of the same duration as the previous run. You would expect that the combined counting rate would be the sum of the individual counting rates. Do your results agree with this expectation? (You may need to consider statistical uncertainties as discussed in Experiment A-2.)

Repeat this experiment with the sources closer to the window, giving higher counting rates. Make each combined run long enough to obtain at least 2000 counts. Finally, take runs with the sources as close to the window as possible without one "hiding" the other.

You probably observed that counts do indeed "add up," if the counting rates are small. When the counting rate is very high, you cannot predict the combined counting rate from the individual counting rates.

In such cases, think of the counter as being overloaded. You can imagine that a short time is required for the counter to respond to each count. At very high counting rates some counts might be lost because they come too close together for the counter to respond. This effect is considered in more detail in an experiment in Section C.

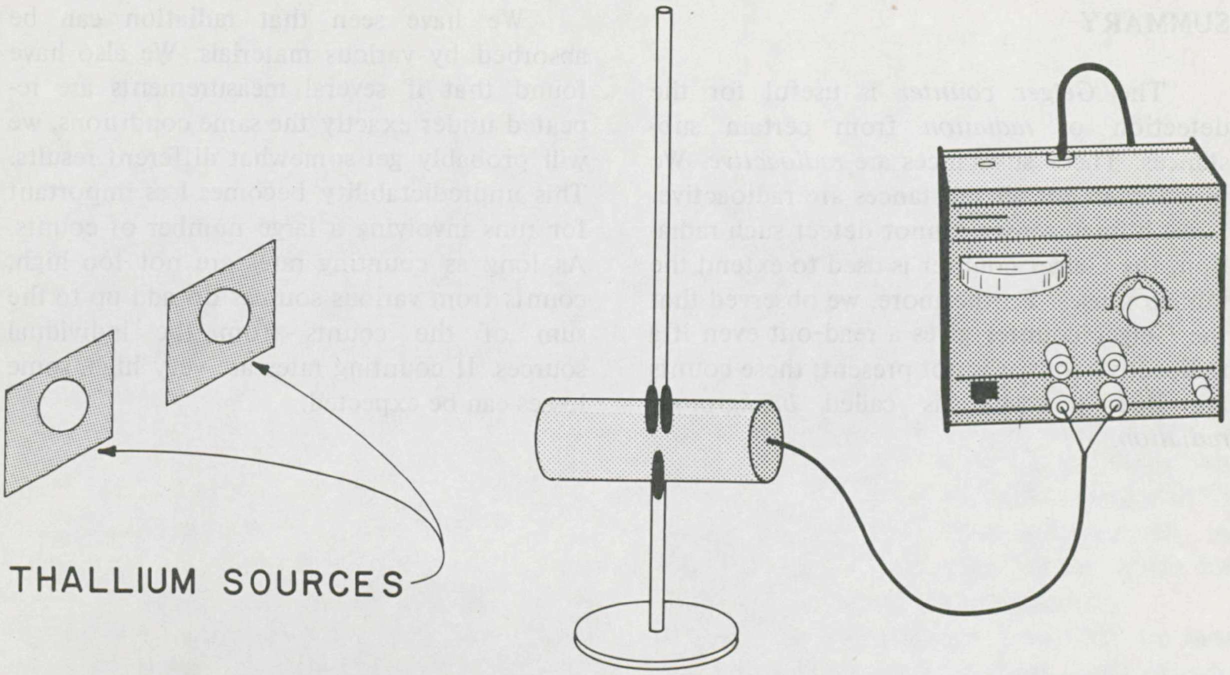

Figure 5. Position of sources for "addition test."

Question 5.

In order to get the true effect of a source, the background radiation must be subtracted. Comment on this in light of Experiment A-3.

A LOOK AHEAD

You are probably wondering why some materials give counts and not others. What is this mysterious *radiation* that you cannot see, hear, feel, or smell, but which, nevertheless, causes counts to be registered? In Section B, we will consider the structure of matter, in order to understand more about such radiation.

So far we have been using the Geiger counter box without knowing how it is constructed or how it operates. This is not an unusual situation; you may not know how an electric clock operates. In Section C, you will have the opportunity to open the Geiger counter box and learn why it responds to radiation.

In the Geiger counter box are located a high voltage power supply and a simple circuit that joins the power supply and Geiger tube. The Geiger tube consists of a cylinder (perhaps 1 centimeter in diameter and 5 centimeters long) with a wire or rod along its axis. The end of the cylinder is covered with a thin "window," often made of aluminum foil or mica, through which radiation particles enter. The power supply "charges" the Geiger tube in such a way that a radiation particle entering the tube triggers an electric current. This current gives rise to an electric pulse which is registered as a count.

SUMMARY

The *Geiger counter* is useful for the detection of *radiation* from certain substances. These substances are *radioactive*. We noted that not all substances are radioactive. Since human senses cannot detect such radiation, the Geiger counter is used to extend the human senses. Furthermore, we observed that the Geiger counter gives a read-out even if a radioactive source is not present; these counts are due to what is called *background radiation.*

We have seen that radiation can be absorbed by various materials. We also have found that if several measurements are repeated under exactly the same conditions, we will probably get somewhat different results. This unpredictability becomes less important for runs involving a large number of counts. As long as counting rates are not too high, counts from various sources do add up to the sum of the counts from the individual sources. If counting rates are very high, some losses can be expected.

SECTION B

Radioactivity and the Nature of Matter

As you have seen, some substances are radioactive while others are not. You also saw that there are at least two kinds of carbon, one that is radioactive and one that is not. In this part of the module we will examine the various kinds of radiation from radioactive materials. We will then try to explain these observations on the basis of a theory of the structure of matter.

RADIOACTIVITY

In order to get a more detailed understanding of radioactivity, it would be helpful to do some experiments with different sources. You will be provided with radioactive sources containing americium-241, thallium-204, and cobalt-60.

You saw in the previous section that radiation can be absorbed. In this experiment you will find out more about this absorption. You will need absorbers made of index card material, aluminum foil, and lead.

EXPERIMENT B-1. Radiation Absorption

Turn on the Geiger counter and prepare to take one-minute runs. The runs to be taken (12 in all) are indicated in Table I. Record your data in a similar table. Study the results and list the three sources in the order of increasing ability to penetrate materials.

You probably wonder why the radiations from the three sources have such different penetrating abilities. Many detailed experiments have shown that we are dealing with three different kinds of radiation. Note that the radiation from the americium has the least penetrating ability. The next more penetrating radiation is that from thallium and the most penetrating is from cobalt. These three kinds of radiation are called respectively, *alpha radiation* (α), *beta radiation* (β), and *gamma radiation* (γ) (making use of the first three letters of the Greek alphabet).

Other experiments have led to more information about these three kinds of radiation. It is now known that alpha radiation and beta radiation both consist of individual small particles. Each has a known, but different, mass and electric charge. The mass of an alpha particle is about 7300 times that of a beta particle.

Electric charge exists in two forms, positive and negative. Ordinary material (such as water, paper, iron, etc.) is uncharged; i.e., we say that it is electrically neutral. This is because it has equal amounts of positive and negative charge.

Alpha radiation consists of identical particles that have a *positive* charge. Beta radiation, on the other hand, can have either positive or negative charge depending on the source; negative is the more common. Gamma

Table I. Form for Data Recording

Source	Counts (no absorber)	Counts (index card)	Counts (aluminum foil)	Counts (lead)
Cobalt-60				
Americium-241				
Thallium-204 #3				

radiation does not have mass or electric charge. It is a form of radiation similar to light, but it is invisible. These characteristics of radiation are summarized in Table II.

Question 6.

Referring to Table II, can you see any correlation between the penetrating ability of a particular kind of radiation and its charge or mass?

Table II. Characteristics of Radiation

Kind of radiation	Penetrating Ability	Mass	Charge
Alpha (α)	least	yes	+
Beta (β)	medium	yes	+ or −
Gamma (γ)	greatest	no	none

THE NATURE OF MATTER

You are probably curious to know why some materials give off radiation while other materials do not. In order to understand this, a brief review of the structure of matter would be helpful.

Most substances are combinations of materials. We use the word *element* to refer to those that are not combinations. Some ordinary substances are elements; for example, metals such as copper, iron, lead, aluminum, and mercury. Many substances are combinations of elements in certain fixed proportions. Such substances are called *compounds.* A single smallest particle of a compound still has this same proportion of elements and is called a *molecule.*

If we subdivide a piece of an element into smaller and smaller pieces, the smallest possible piece which still has the properties of the material is an *atom.* If we did this for a compound, we would end up not with an atom, but with a *molecule.* Thus, if we subdivide a piece of copper into smaller and smaller pieces, we eventually obtain an atom of copper. If, however, we subdivide water into smaller and smaller amounts, we eventually arrive at one molecule of water. This molecule consists of a combination of hydrogen and oxygen atoms. These ideas are represented in the diagrams of Figure 6.

We now know of about 100 elements in all. A few of these are man-made. Others are found in the natural world. The number of possible combinations of elements into compounds seems to be endless. All known substances are combinations of these elements.

You may wonder if the atom can be further subdivided. This is an especially good question, since the word *atom* comes from a Greek word meaning *indivisible.* However, in the 20th century it has become possible to subdivide the atom. When this happens, the result is no longer an atom of the element. For example, when an iron atom is subdivided, the result is no longer ordinary iron.

Many experiments done over the years have shown that atoms are made of three smaller particles: *electrons, protons,* and *neutrons.* The protons and neutrons are packed closely together in what is called the *nucleus* (in the center of the atom) and the electrons are in a kind of fuzzy "cloud" surrounding the nucleus, as indicated in Figure 7. (Actually, because they are so small, our mental

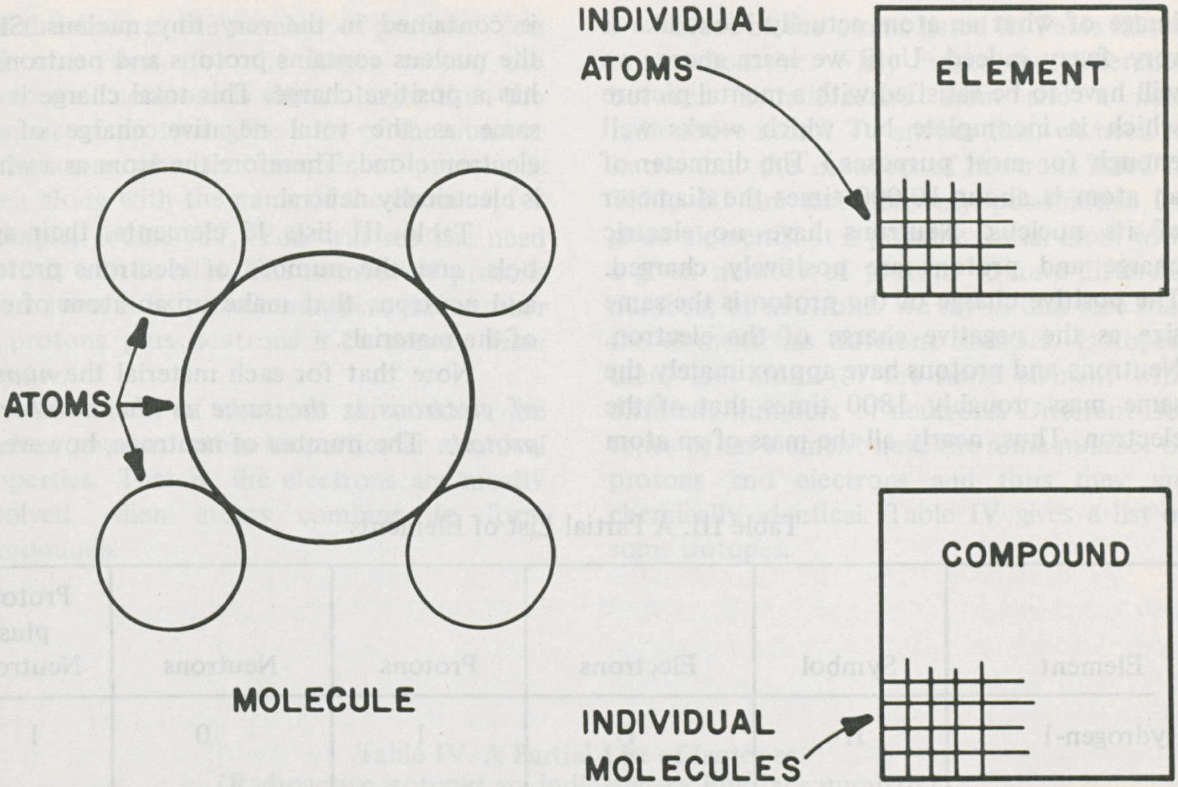

Figure 6. Relationships among elements, compounds, atoms, and molecules.

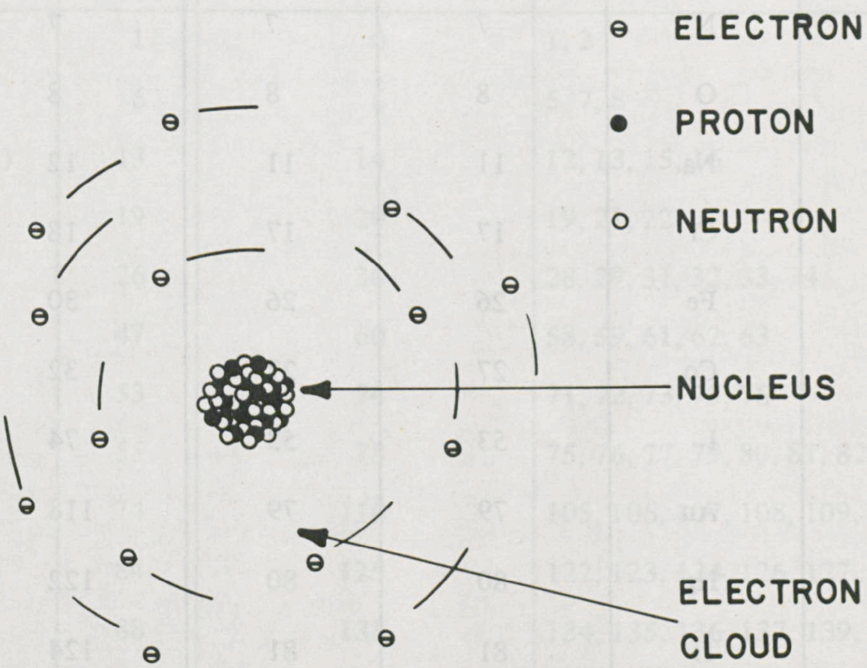

Figure 7. Our mental picture of a large atom.

image of what an atom actually looks like is very fuzzy indeed. Until we learn more, we will have to be satisfied with a mental picture which is incomplete but which works well enough for most purposes.) The diameter of an atom is about 10,000 times the diameter of its nucleus. Neutrons have no electric charge and protons are positively charged. The positive charge of the proton is the same size as the negative charge of the electron. Neutrons and protons have approximately the same mass, roughly 1800 times that of the electron. Thus, nearly all the mass of an atom is contained in the very tiny nucleus. Since the nucleus contains protons and neutrons, it has a positive charge. This total charge is the same as the total negative charge of the electron cloud. Therefore the atom as a whole is electrically neutral.

Table III lists 16 elements, their symbols, and the number of electrons protons, and neutrons that make up an atom of each of the materials.

Note that for each material the *number of electrons is the same as the number of protons.* The number of neutrons, however, is

Table III. A Partial List of Elements

Element	Symbol	Electrons	Protons	Neutrons	Protons plus Neutrons
Hydrogen-1	H	1	1	0	1
Helium-4	He	2	2	2	4
Carbon-12	C	6	6	6	12
Nitrogen-14	N	7	7	7	14
Oxygen-16	O	8	8	8	16
Sodium-23	Na	11	11	12	23
Chlorine-35	Cl	17	17	18	35
Iron-56	Fe	26	26	30	56
Cobalt-59	Co	27	27	32	59
Iodine-127	I	53	53	74	127
Gold-197	Au	79	79	118	197
Mercury-202	Hg	80	80	122	202
Thallium-205	Tl	81	81	124	205
Lead-208	Pb	82	82	126	208
Uranium-238	U	92	92	146	238
Americium-241	Am	95	95	146	241

not the same as the number of protons. You will note that, for the larger atoms, the number of neutrons is always larger than the number of protons. The sum of the number of neutrons plus the number of protons is given along with the name of the element; for example, iodine-127. You will see the need for this a little later. The number of protons in an atom is its *atomic number*; the number of protons plus neutrons is its *atomic mass number.*

The cloud of electrons surrounding the nucleus gives an atom its particular chemical properties. That is, the electrons are mostly involved when atoms combine to form compounds.

Most of the atoms listed in Table III are not radioactive. What makes the difference between a radioactive atom and a non-radioactive atom? To answer this, we need to know that the numbers of neutrons listed in Table III are not the only possibilities for given elements. It is possible for an atom with a given number of protons to have different numbers of neutrons. We say in that case that the element has different *isotopes.* Isotopes, then, are atoms of the *same* element with different numbers of neutrons. Different isotopes of an element have the same number of protons and electrons and thus they are chemically identical. Table IV gives a list of some isotopes.

Table IV. A Partial List of Isotopes
(Radioactive isotopes are indicated by boldface numbers)

Element	Protons	Neutrons (Most common isotopes)	Neutrons (Other isotopes)
Hydrogen (H)	1	0	**1**, 2
Carbon (C)	6	6	**5**, 7, **8**
Aluminum (Al)	13	14	**12**, **13**, **15**, **16**
Potassium (K)	19	20	**19**, 21, **22**
Iron (Fe)	26	30	28, **29**, 31, 32, **33**, **34**
Silver (Ag)	47	60	**58**, **59**, **61**, 62, **63**
Iodine (I)	53	74	**71**, **72**, **73**, **75**, **76**
Cesium (Cs)	55	78	**75**, **76**, **77**, **79**, **80**, **81**, **82**
Tungsten (W)	74	110	**105**, 106, **107**, 108, 109, **111**, **112**, **113**
Polonium (Po)	84	**125**	**122**, **123**, **124**, **126**, **127**, **128**
Radium (Ra)	88	**138**	**134**, **135**, **136**, **137**, **139**, **140**
Thorium (Th)	90	**142**	**139**, **140**, **141**, **143**, **144**
Uranium (U)	92	**146**	**143**, **144**, **145**, **147**, **148**
Americium (Am)	95	**146**	**142**, **143**, **144**, **145**, **147**, **148**, **149**, **150**
Californium (Cf)	98	**153**	**151**, **152**, **154**, **155**, **156**

A particular isotope of an element is designated in various ways. For example, the isotope of iodine which has 72 neutrons can be indicated by any of the following notations: iodine-125, ^{125}I, $^{125}_{53}I$, or $_{53}I^{125}$.

Isotopes of atoms are also classified as *stable* or *unstable.* Stable atoms are not radioactive and unstable atoms are radioactive. An unstable atom emits some kind of radiation (usually α, β, or γ) and we say that it *decays* in the process. We call the process *radioactive decay.* A new atom is formed by the decay process and this new atom may itself be either stable or unstable. If it is unstable, it will later decay, and the process continues until a stable atom results.

By examining Table IV, you can draw two conclusions: (1) except for atoms with large numbers of protons, the most common isotope of an element is stable; (2) very few other isotopes are stable. Naturally occurring atoms are generally stable. This is because the unstable atoms which were formed long ago have mostly decayed, eventually leaving stable atoms. (The reason for the exceptions will be discussed later.)

We should now consider what happens to an atom when α, β, or γ radiation is emitted.

Question 7.

According to Table III, the oxygen nucleus has 8 protons and 8 neutrons. Another nucleus has 8 protons and 7 neutrons. Is this also oxygen? Why?

ALPHA PARTICLES

Alpha particles (α) are identical to the nuclei of helium atoms. That is, an alpha particle is just like a helium atom which has had its electrons removed. Each alpha particle consists of 2 protons and 2 neutrons. Therefore, if an atom emits an alpha particle, the nucleus loses 2 protons and 2 neutrons. That means that the atom which remains is no longer the same element, since its atomic number is now smaller than that of the original atom.

As an example, consider the radioactive decay of polonium-210 ($_{84}Po^{210}$). An alpha

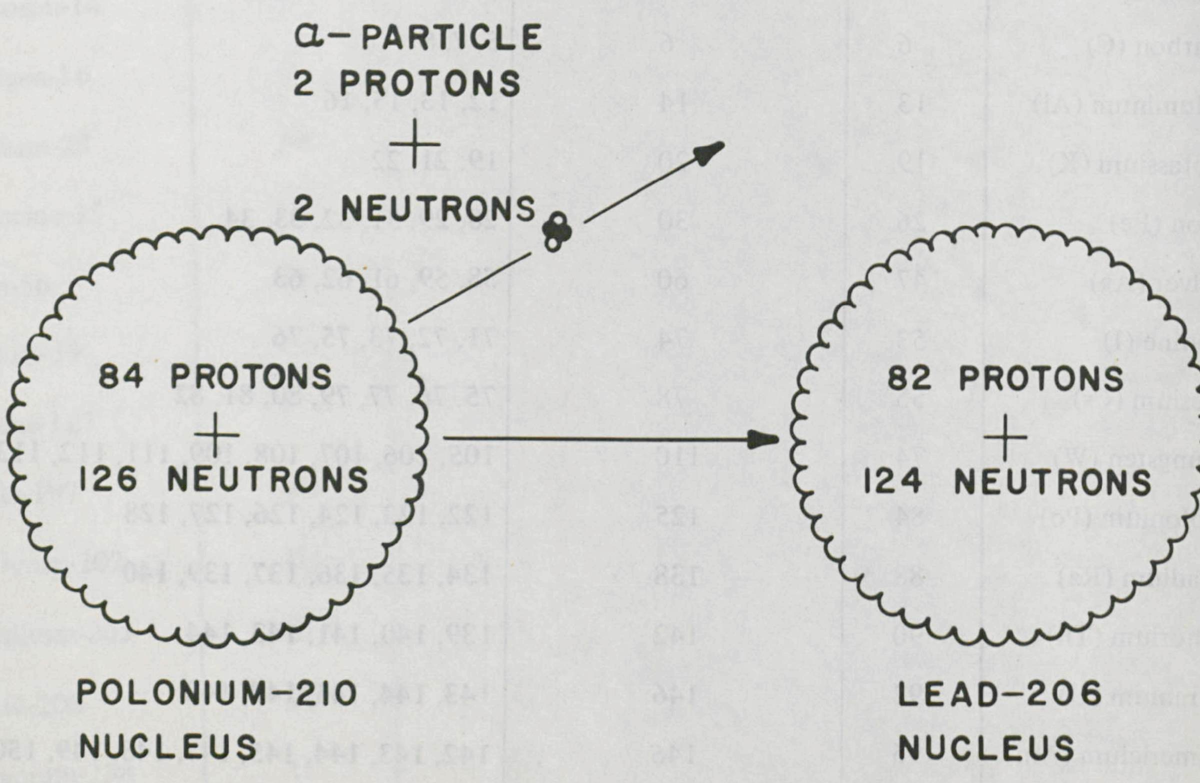

Figure 8. Diagram of polonium-210 decay.

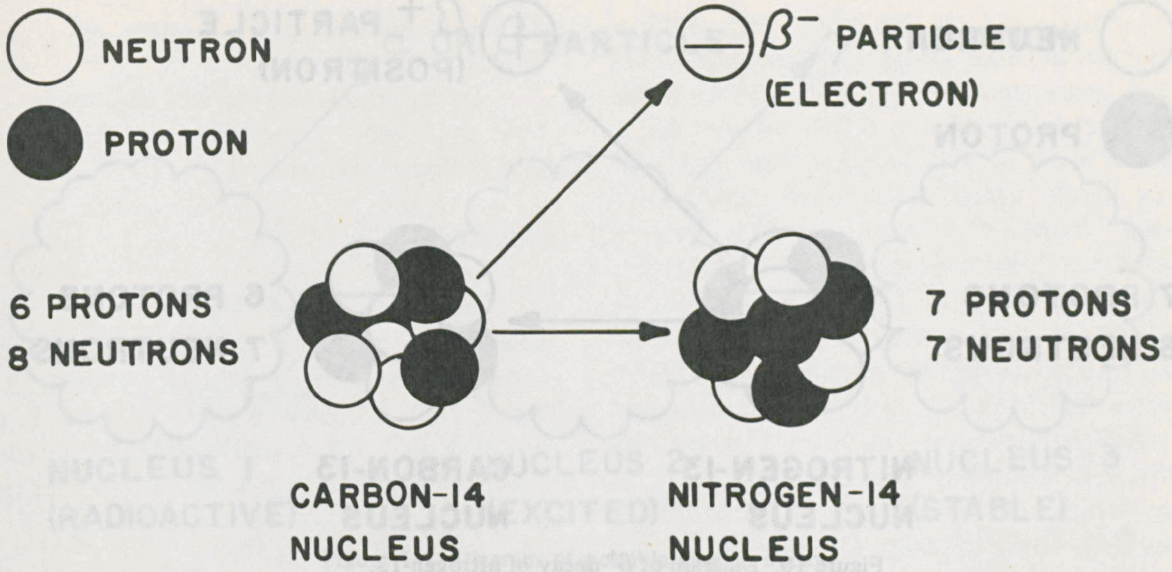

Figure 9. Diagram of carbon-14 decay.

particle is emitted, which decreases the atomic number by 2. The polonium nucleus contains 84 protons and 126 neutrons (note that $84 + 126 = 210$). The new nucleus has 82 protons and 124 neutrons. This is an isotope of lead, $_{82}Pb^{206}$. (See Figure 8.)

Alpha emission is especially common among unstable atoms with high atomic number. Examples are: americium, uranium, radium, polonium, radon, and throium.

As mentioned earlier, the new element formed by radioactive decay might also be unstable, and a new decay will then take place afterward. Actually, polonium is the next-to-the-last stage of a very long *radioactive series*, which starts with uranium-238 and ends with the stable isotope lead-206. Radium is an earlier stage than polonium of the same series. This means that a sample of radium normally contains not only radium but other elements resulting from successive radioactive decays. Some radioactive isotopes emit beta and gamma radiations, and, therefore, a radium sample is not a pure source of alpha particles; betas and gammas are also emitted.

Question 8.

Suppose a radon-222 nucleus (86 protons) undergoes alpha decay. What are the numbers of protons and neutrons in the newly formed nucleus?

BETA PARTICLES

Beta radiation (β) consists of particles with the same mass and the same amount of charge as ordinary electrons, but some are positive and some are negative. We can therefore think of beta particles as positive or negative electrons. (The positive electron is also called a *positron*.)

In order to investigate beta decay, let us use carbon-14 as an example. Carbon has 6 protons in its nucleus. The most common number of neutrons is also 6. Carbon-14 has 8 neutrons. It is often the case for isotopes with a "surplus" of neutrons that negative beta decay occurs. That is, a β^- particle is emitted by the nucleus. We can think of a neutron in the nucleus as being somehow transformed into a proton and a negative electron,* with the latter being thrown out of the nucleus at high speed. This leaves the nucleus with 7 protons and 7 neutrons. This combination is nitrogen-14, which is stable. (See Figure 9.)

*Still another particle is involved, called an *antineutrino*. It is a particle with no charge and is emitted along with the electron. Geiger counters cannot detect it.

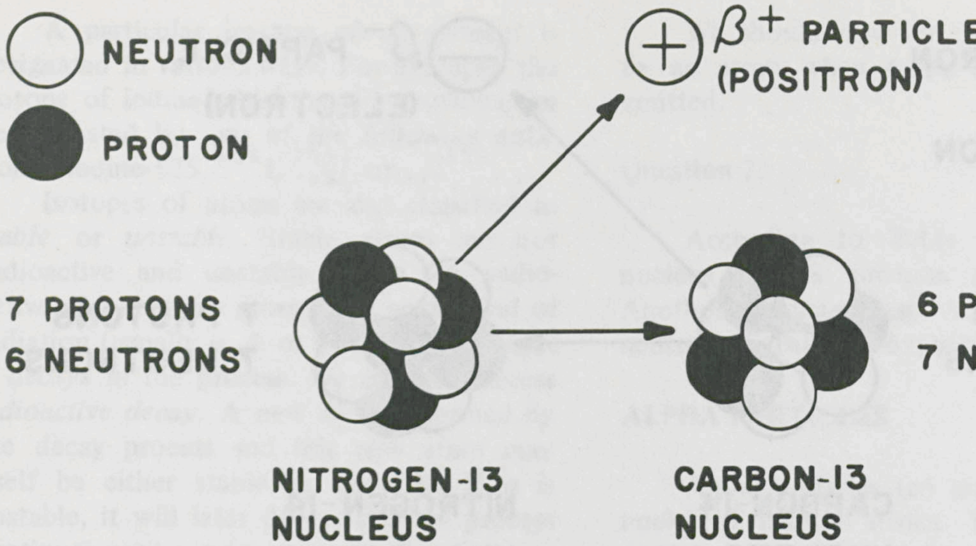

Figure 10. Diagram of β^+ decay of nitrogen-13.

If the nucleus has a "deficit" of neutrons (fewer than the most common number), then a positive beta particle (β^+) is often emitted. In this case, we can imagine that a proton is transformed into a neutron and a positive electron,* with the latter thrown out at high speed. An example of this is nitrogen-13 (7 protons and 6 neutrons). The most common neutron number for nitrogen is 7. An emitted positive beta particle leaves 6 protons and 7 neutrons, which is the stable isotope carbon-13. (Figure 10.)

Question 9.

In some cases it is possible for a nucleus to "swallow up" one of the electrons from the cloud surrounding it–a kind of reverse beta decay which is called *orbital capture.* A gamma ray is then emitted. Does the atomic number change? Does the atomic mass number change?

Question 10.

Tellurium-131 (52 protons) decays by negative beta emission. How many protons and neutrons does the new nucleus have? Can you identify this new nucleus from Table IV?

*In this case another particle, called the *neutrino,* is emitted along with the positive electron. The neutrino is similar to the anitneutrino.

GAMMA RAYS

Gamma rays (γ) most often arise as secondary radiation, following beta or alpha decay. An atom first emits an alpha or beta particle and the resulting nucleus is unstable. The nucleus is left in an *excited state,* which means that it has excess energy to get rid of. The emission of the gamma ray results in an atom of the same element and even the same isotope. It too may be unstable and, if so, it will decay again later. (See Figure 11.)

Cobalt-60, which you used in Experiment B-1 as a source of gamma rays, is itself a negative beta emitter. (This beta particle moves slowly and therefore has very low penetrating ability.) The resulting nucleus (nickel-60) is in an excited state and emits two gamma rays before achieving stability. Sources which produce only gamma radiation are rare.

CHANGES IN THE ELECTRON CLOUD

Consider again the beta decay of carbon-14, to form nitrogen-14. Carbon has 6 protons in its nucleus and 6 electrons in the electron cloud around its nucleus. On the other hand, an ordinary nitrogen atom has 7 protons and 7 electrons. When the nucleus changes from carbon to nitrogen, what happens to the electron cloud? The net positive

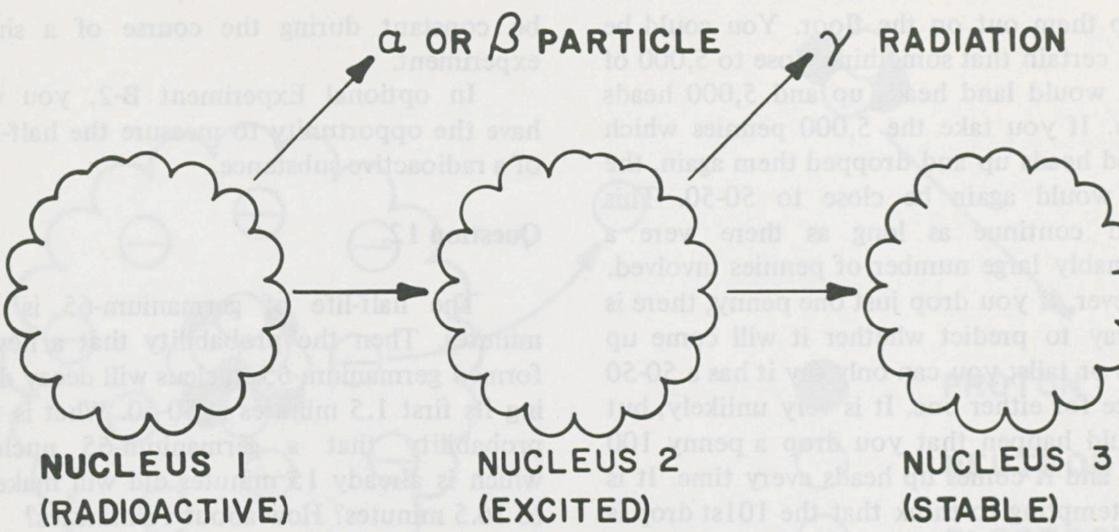

Figure 11. Diagram of possible gamma decay.

charge of the atom will attract a "stray" electron. This electron will be added to the cloud, and the atom will then be a neutral nitrogen atom.

In the case of nitrogen-13 considered earlier, positive beta decay decreases the proton number and thus the cloud afterward contains a surplus of electrons. The extra electron is no longer held firmly in the atom and it will soon escape and simply be added to the supply of stray electrons in the material.

In all cases involving beta or alpha decay, such changes will eventually take place in the electron cloud to accommodate the change in atomic number.

Since an alpha particle is itself a helium nucleus, it will eventually pick up two electrons and become an ordinary helium atom.

Question 11.

Discuss what happens to the electron cloud of an atom after it emits an alpha particle. Do the same for an atom which emits a gamma ray.

TIME IN RADIOACTIVE DECAY

Given a radioactive isotope, how much time will elapse before it decays? There is no way of knowing precisely. It may happen immediately and it may be a very long time indeed. It is possible, however, to be more definite when we are dealing with a large number of identical atoms.

If at any time we know that there are a given number of radioactive atoms (call it N), then at some later time, we would find that half of the atoms will have decayed. This time period, called the *half-life* ($T_{1/2}$), is found to be the same for that particular isotope, regardless of how much there is of it at the start.* For example, if the half-life is 2 hours, then after 2 hours half of the atoms will remain undecayed. After another 2 hours (4 hours from the start), one quarter of the atoms will remain, etc.

It is important to remember that we can describe radioactive decay only in a statistical way or for large numbers of atoms. For example, if we could observe a single atom of a radioactive substance, we might ask just when it will decay. There is no way to answer such a question other than state what its chances of decay are while we are watching it.

It is something like the following experiment, which you could do. Suppose you have $100 worth of pennies in a bag, and you

*We are assuming that the number of atoms is very large. Because statistical uncertainties are always present, these statements are not strictly true if the number of atoms is small.

dump them out on the floor. You could be quite certain that something close to 5,000 of them would land heads up and 5,000 heads down. If you take the 5,000 pennies which landed heads up and dropped them again, the split would again be close to 50-50. This would continue as long as there were a reasonably large number of pennies involved. However, if you drop just one penny, there is no way to predict whether it will come up heads or tails; you can only say it has a 50-50 chance for either one. It is very unlikely, but it could happen that you drop a penny 100 times and it comes up heads every time. It is then tempting to think that the 101st drop is bound to come up tails, but that is *not* the case; the probability is still 50-50.

So it goes also with radioactive atoms. Thus, radioactive samples do not "age" in the biological sense of that word. An adult biological organism is more likely to die the older it becomes. A radioactive atom that has survived for many years has no more chance of decaying in the next minute than one (of the same isotope) that was formed immediately beforehand. (Radioactive decay also does not normally decrease the size of a sample. New atoms that are formed by the decay process take up about as much space as the original atoms.)

Isotopes differ very widely in the value of their half-lives, ranging from small fractions of a second to billions of years. Radioactive isotopes which are found in nature either have very long half-lives or have resulted from the radioactive decay of isotopes that do have long half-lives. For example, radium found in natural deposits has a half-life of about 1620 years. Radium would therefore have disappeared long ago if it were not continually replenished by the radioactive decay of heavier elements. The radioactive chain starts with uranium-238, which has a half-life of 4.51 billion years. No element heavier than uranium has a long enough half-life to have survived in appreciable quantities since the formation of the earth. If the half-life of a radioactive sample is several months or more, one may consider its average rate of decay to be constant during the course of a short experiment.

In optional Experiment B-2, you will have the opportunity to measure the half-life of a radioactive substance.

Question 12.

The half-life of germanium-65 is 1.4 minutes. Then the probability that a newly formed germanium-65 nucleus will decay during its first 1.5 minutes is 50-50. What is the probability that a germanium-65 nucleus which is already 15 minutes old will make it to 16.5 minutes? How about 18 minutes?

Problem 4.

If the half-life of a radioactive isotope is 1.5 hours, what fraction of the original atoms will still be in a sample after 7.5 hours?

PENETRATING ABILITY OF THE DIFFERENT KINDS OF RADIATION

Earlier in this section a question was raised about the reason for the widely different penetrating abilities of alpha, beta, and gamma radiations. Now that you understand more about the nature of these kinds of radiation, you are in a position to consider this question.

Radiation entering a material is at least partially absorbed by the material. The absorption of radiation depends on the extent to which the radiation interacts with the atoms of the absorbing material. The greater the degree of interaction, the greater the absorption and the smaller the penetrating ability.

Let us consider first the cases of alpha and beta radiations, since these both consist of charged particles. It was pointed out earlier that atoms are normally electrically neutral. However, if a charged particle (α or β) passes near an atom, then the passing particle exerts an electric force on individual electrons of the atom. Those electrons on the near side of the atom experience the greatest force (Figure

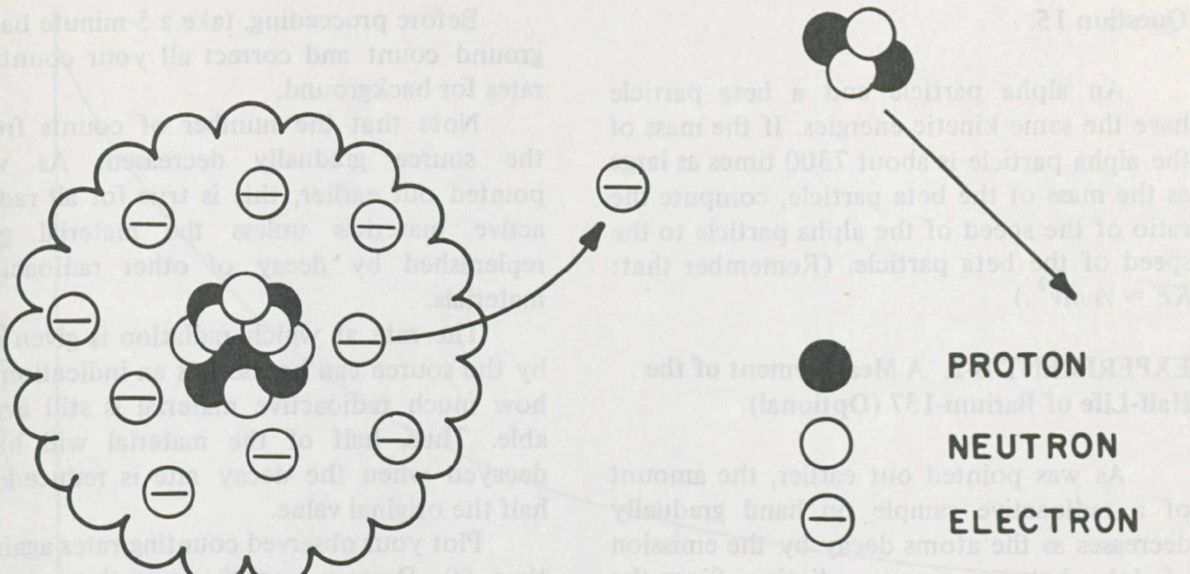

Figure 12. A charged alpha particle passing near an atom.

12). Often this force can be great enough to remove an electron from the atom. We say in that case that the atom is *ionized.*

During the ionization process, the passing particle loses kinetic energy, since it must do work in order to remove an electron from the atom. Usually this loss of kinetic energy is very small. Therefore, the moving particle can cause thousands, perhaps millions, of ionizations before it comes to rest.

The force exerted on the electron depends on the charge of the passing particle (and on the charge of the electron). The greater the charge, the greater the force exerted. But the "damage" done to the atom depends not only on the amount of force but also on the time during which the force acts. A slowly moving particle is in the vicinity of a particular atom longer than a rapidly moving particle and is therefore more likely to cause ionization.

Recall that the alpha particle has twice the charge of a beta particle. It also has a mass about 7300 times that of the beta particle. Therefore, if the kinetic energies are not too different, the alpha particle moves much more slowly. Thus, the alpha particle causes more ionizations for both reasons: it has greater charge and slower speed. If it causes more ionization, it will be brought to rest sooner, i.e., it has less penetrating ability.

Gamma radiation does not consist of charged particles. At the energies considered in this module, it has only a very weak interaction with electrons and consequently causes few ionizations (compared with alpha or beta particles). Thus, its greater penetrating ability is understandable.

All three kinds of radiation (α, β, and γ) can be registered by a Geiger counter because these radiations cause ionization as discussed above. How ionization causes the counter to respond will become clear in Section C.

Question 13.

How would the numbers in Table III be incorrect for ionized atoms?

Question 14.

In the absorption experiment you did, Experiment B-1, list the absorbers in the order of increasing ability to absorb radiation. Can you relate this list to the amount of material the radiation must penetrate in order to get through each absorber?

Question 15.

An alpha particle and a beta particle have the same kinetic energies. If the mass of the alpha particle is about 7300 times as large as the mass of the beta particle, compute the ratio of the speed of the alpha particle to the speed of the beta particle. (Remember that: $KE = \frac{1}{2} mv^2$.)

EXPERIMENT B-2. A Measurement of the Half-Life of Barium-137 (Optional)

As was pointed out earlier, the amount of a radioactive sample on hand gradually decreases as the atoms decay by the emission of alpha, beta, or gamma radiation. Since the number of particles radiated depends on the amount of the radioactive material on hand, the number of counts that can be registered by a Geiger counter also gradually decreases. In fact, these two quantities go hand in hand. By studying the decrease in the counting rate we can therefore draw conclusions about the amount of the material still in the sample.

A practical laboratory experiment on half-life requires that the radioactive sample have a half-life of not more than a few hours, and preferably it should be only a few minutes. Such sources obviously become useless after a few days. Thus, the short half-life material must be produced immediately before the experiment.

In this experiment, cesium-137, with a half-life of about 30 years, decays into barium-137, by the emission of a beta particle. Barium-137 has a short half-life (a few minutes) and decays by emitting gamma radiation, becoming a stable form of barium-137. The barium is separated from the cesium by chemical means. Your instructor will either perform the separation or give you explicit directions about how to do it.

Arrange the Geiger counter for making a run and put a drop or two of barium-137 near the window. You will need to measure time intervals Δt and also running time t. It is suggested that you take a 15-second run every 30 seconds for a total of 10 minutes (20 runs altogether).

Before proceeding, take a 5-minute background count and correct all your counting rates for background.

Note that the number of counts from the source gradually decreased. As was pointed out earlier, this is true for all radioactive materials unless the material gets replenished by decay of other radioactive materials.

The rate at which radiation is given off by the source can be used as an indication of how much radioactive material is still available. Thus, half of the material will have decayed when the decay rate is reduced to half the original value.

Plot your observed counting rates against time (t). Draw a smooth curve through the points. Your curve should be similar to that shown in Figure 13.

From your graph, read off the time at which the counting rate was one half the starting value. Now take some new starting value (another point on the curve). After how much time did the counting rate reach half *that* value? Do this for at least three starting points on the curve. Do you obtain approximately the same time in each case?

The time required for half the material to decay is the same as the half-life of that radioactive material defined earlier.

Compute the time required for the decay rate of your sample to decrease by a factor of 256. How many half-lives is this?

SUMMARY

In this section you identified three different kinds of radiation (*alpha, beta,* and *gamma*), having widely different penetrating abilities. *Alpha radiation* consists of charged particles that can be identified as *helium nuclei. Beta radiation* consists of *negative or positive electrons. Gamma radiation* has no charge or mass and it has many of the properties of light.

Alpha particle emission leaves an atom with its atomic number decreased by two. When a positive beta particle is emitted, the

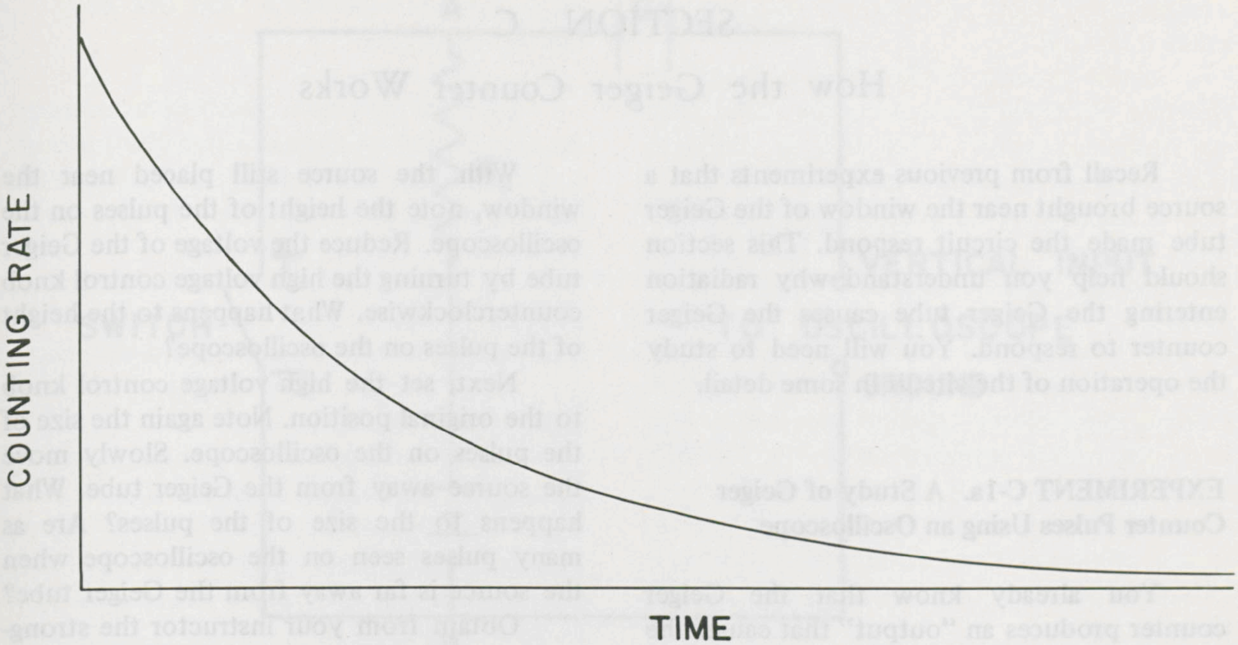

Figure 13. Sample decay curve.

atomic number of the atom decreases by one. When a negative beta particle is emitted, the atomic number increases by one. Gamma ray emission does not change the atomic number.

Often the new atom formed by radioactive decay is also *unstable* and further decay will later take place. The end product (after many steps, in some cases) is a *stable isotope*.

The term *half-life* indicates the period of time during which half of the initial number of atoms of a radioactive material decay.

SECTION C

How the Geiger Counter Works

Recall from previous experiments that a source brought near the window of the Geiger tube made the circuit respond. This section should help you understand why radiation entering the Geiger tube causes the Geiger counter to respond. You will need to study the operation of the circuit in some detail.

EXPERIMENT C-1a. A Study of Geiger Counter Pulses Using an Oscilloscope

You already know that the Geiger counter produces an "output" that causes the scaler to respond, a radio to click, or a meter to register. A cathode ray oscilloscope permits us to *see* the output. In this experiment you will study the output of the Geiger counter and find out how it varies as you change various things in the set-up.

Connect the input terminals of the oscilloscope to the Geiger counter where the scale was connected before. Adjust the oscilloscope to get a clear horizontal trace. Turn on the Geiger counter and bring a source close to the window of the Geiger tube. You should observe voltage pulses similar to those shown in Figure 14.

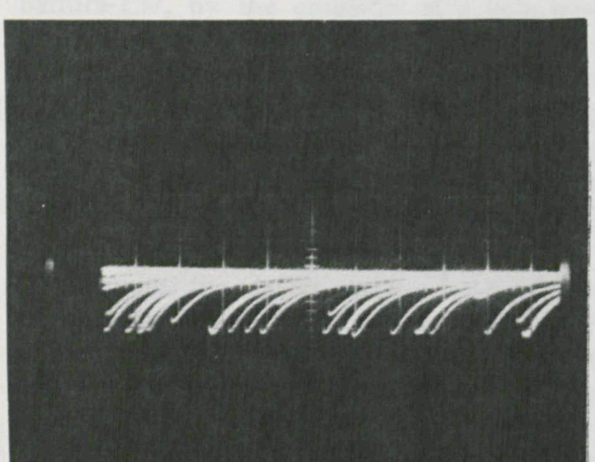

Figure 14. Oscilloscope trace of pulses from a Geiger counter.

With the source still placed near the window, note the height of the pulses on the oscilloscope. Reduce the voltage of the Geiger tube by turning the high voltage control knob counterclockwise. What happens to the height of the pulses on the oscilloscope?

Next, set the high voltage control knob to the original position. Note again the size of the pulses on the oscilloscope. Slowly move the source away from the Geiger tube. What happens to the size of the pulses? Are as many pulses seen on the oscilloscope when the source is far away from the Geiger tube?

Obtain from your instructor the strongest source available and repeat these observations. You probably noticed that, at very high pulse rates, some pulses were smaller and oddly shaped. We will discuss this later. Do the pulses otherwise look about the same?

You will next study how the pulse size depends on the energy* of the radiation entering the Geiger tube. Obtain a thallium-204 source (maximum beta energy 0.76 MeV*) and a strontium-90 source (maximum beta energy 2.2 MeV). Compare the heights of the pulses produced from each of these sources. What is the relationship between particle energy and pulse height?

Finally, we will compare the pulses produced by two different kinds of radiation. Obtain a cobalt-60 (gamma) source and a strontium-90 (beta) source. With the Geiger counter still set up as for previous experiments, first place the cobalt-60 source near the window, note the height of the pulses on the oscilloscope. Then, try the same observation using the strontium-90 source. Is there any difference in the pulse heights produced?

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*The energy of a beta particle or an alpha particle is a measure of how fast it is moving and is usually measured in million electron volts (MeV). An electron volt (eV) is the amount of energy an electron would gain if it were propelled from a negatively-charged metal plate to a positively-charged one if the voltage across the plates is one volt.

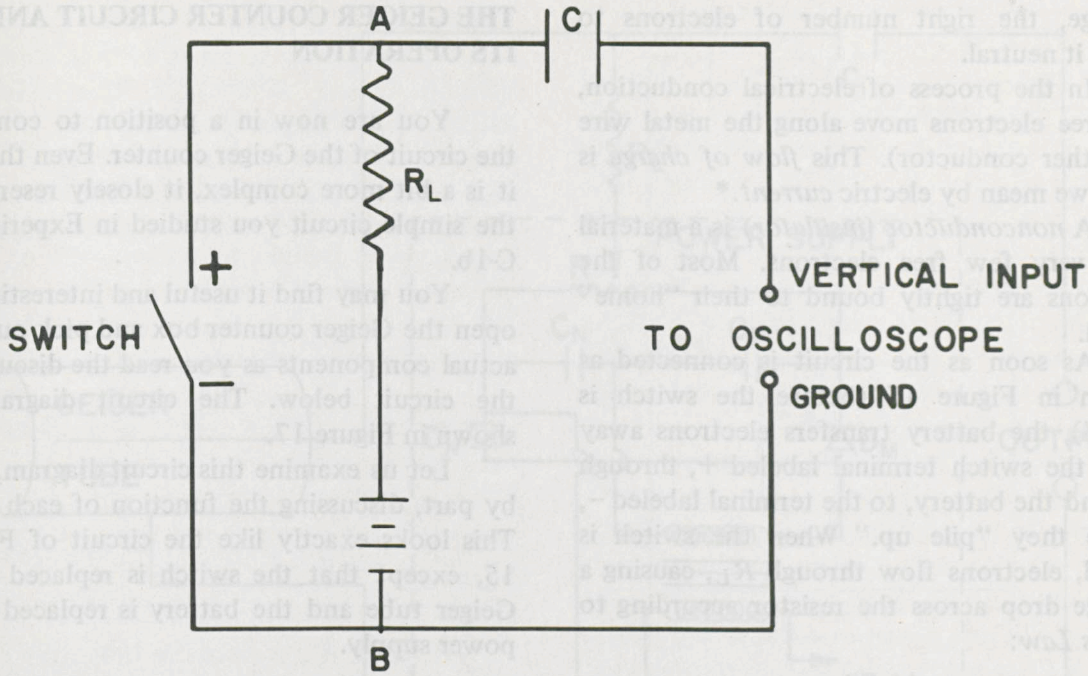

Figure 15. Diagram of a circuit to show pulses.

Question 16.

From your observations make a summary statement about what affects the pulse height.

EXPERIMENT C-1b. Pulses from a Simple Circuit

In order to understand how the Geiger counter circuit causes the pulses you observed with the oscilloscope, it would be helpful to experiment with the circuit illustrated in Figure 15. The suggested components are: a 115-volt battery, a 10-megohm resistor, a 0.1-microfarad capacitor, a "momentary" switch, and an input to the oscilloscope.

Immediately after the switch is closed, you should see on the oscilloscope screen a pulse something like that shown in Figure 16. Do this repeatedly by opening and closing the switch in rapid succession.

Note that the pulses are negative and that they rise back to zero after a very short period of time. In general, the pulses have about the same shape as those from the Geiger counter.

Now, replace the 1.5-volt battery with a 6-volt battery and repeat the observations. How do the pulse sizes compare?

To understand how these pulses arise, let us consider how charge flows in metals.

As was pointed out earlier, all materials are normally electrically neutral. This means that in the neighborhood of each atomic nucleus there is the right number of electrons needed to make the atom electrically neutral (i.e., the number of electrons surrounding the nucleus equals the number of protons in the nucleus). For most metals (*conductors*), some electrons are very loosely bound to the "home" nucleus and they can wander about from atom to atom. These are called *free electrons.* Each nucleus still has near it, on the

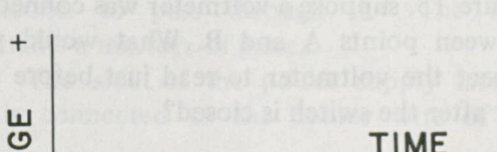

Figure 16. Sketch of a single voltage pulse.

average, the right number of electrons to make it neutral.

In the process of electrical conduction, the free electrons move along the metal wire (or other conductor). This *flow of charge* is what we mean by electric *current*.*

A *nonconductor* (*insulator*) is a material with very few free electrons. Most of the electrons are tightly bound to their "home" nuclei.

As soon as the circuit is connected as shown in Figure 15 (before the switch is closed), the battery transfers electrons away from the switch terminal labeled +, through R_L and the battery, to the terminal labeled −, where they "pile up." When the switch is closed, electrons flow through R_L, causing a voltage drop across the resistor according to *Ohm's Law*:

$$V = IR_L$$

Here, R_L is the value of the resistance (in ohms), I is the current (in amperes) and V is the voltage (in volts). The oscilloscope is connected to the circuit by way of the capacitor C. The capacitor serves the function of blocking the steady voltage of the battery from affecting the oscilloscope. When the switch is open, the side of the capacitor which is connected to the resistor (point A) is at 1.5 volts or 6 volts, depending on the battery used. However, when the switch is closed, that point suddenly drops to 0 volts, and a short pulse gets through the capacitor to the scope. This is the negative pulse that one sees.

Question 17.

In the "switch-controlled circuit" of Figure 15, suppose a voltmeter was connected between points A and B. What would you expect the voltmeter to read just before and just after the switch is closed?

*Electric current is the amount of charge that flows in one second.

THE GEIGER COUNTER CIRCUIT AND ITS OPERATION

You are now in a position to consider the circuit of the Geiger counter. Even though it is a bit more complex, it closely resembles the simple circuit you studied in Experiment C-1b.

You may find it useful and interesting to open the Geiger counter box and pick out the actual components as you read the discussion the circuit below. The circuit diagram is shown in Figure 17.

Let us examine this circuit diagram, part by part, discussing the function of each part. This looks exactly like the circuit of Figure 15, except that the switch is replaced by a Geiger tube and the battery is replaced by a power supply.

POWER SUPPLY

The power supply provides a voltage to operate the rest of the circuit. It operates on 115-volt alternating current, as is common in our homes. The input voltage is increased by a transformer to a value high enough to operate the Geiger tube. Following the secondary side of the transformer, we see two diodes (D_M and D_N) and two capacitors (C_M and C_N). These diodes and capacitors change the alternating current to direct current and double the output voltage of the transformer. Next, there is a resistor labeled R. In the diagram, an arrow points to the center portion of this resistor. This indicates that the contact point to R can be varied so that the amount of voltage applied to the remainder of the circuit can be selected. As you rotated the voltage control knob in earlier experiments, the voltage was being varied by moving this point of contact.

The components of the circuit mentioned thus far are all inside the dotted line of our diagram. This portion of the circuit is the power supply for the Geiger counter. We will simplify our diagram by using a box with

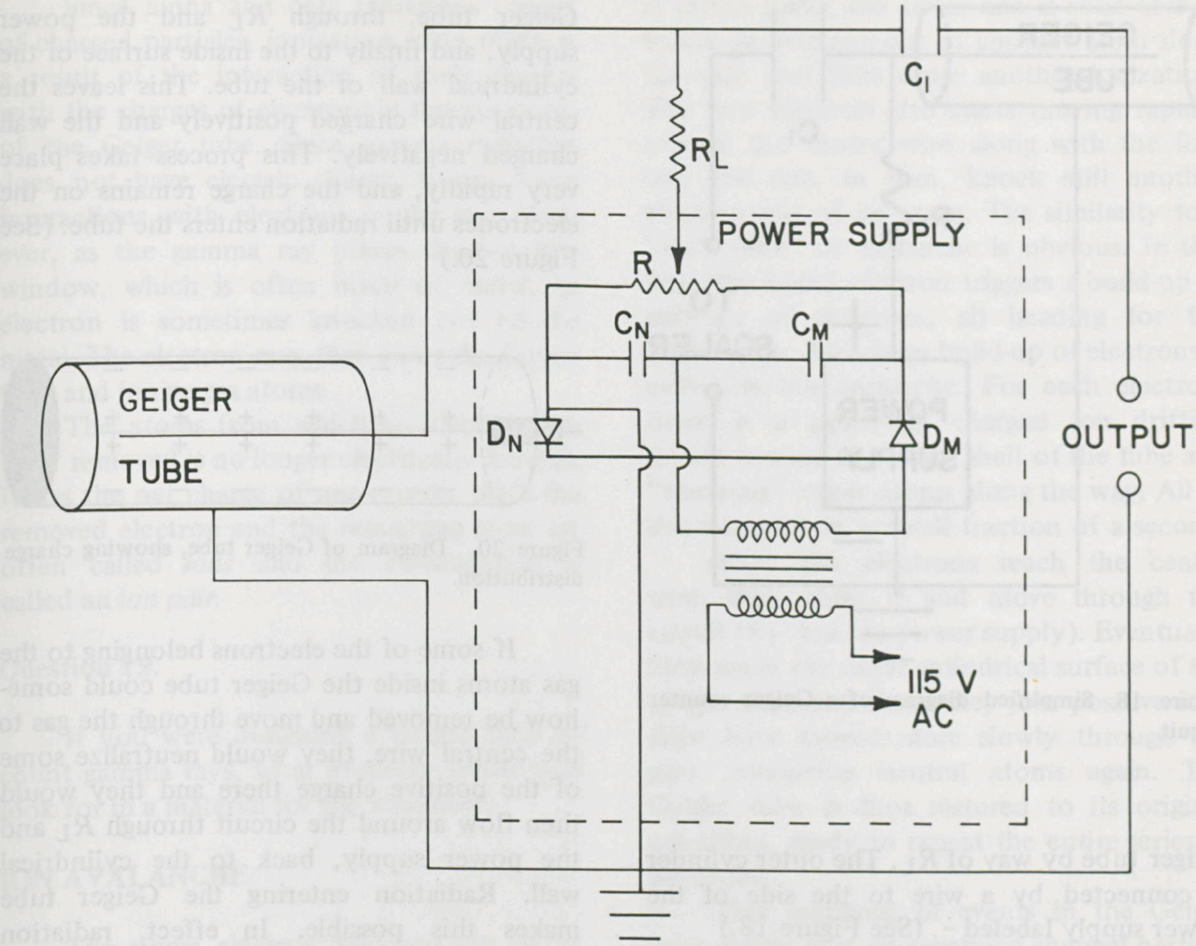

Figure 17. Diagram of a Geiger counter circuit.

power supply written on it to represent the circuitry of the power supply.

This simplified diagram makes it more obvious that this is very similar to the simple circuit of Figure 15, where the Geiger tube replaces the switch and the power supply replaces the battery.

How the Geiger tube functions to "close the switch" will be discussed in some detail.

Problem 5.

Let us assume that R_L in the Geiger counter circuit has a value of 5 megohms (55×10^6 ohms). How great is the current if a voltage pulse of 10 volts is observed across R_L?

THE GEIGER TUBE

A typical Geiger tube consists of a metal cylinder with a wire or rod that is insulated from the cylinder along its center line. (See Figure 19.) The cylinder and wire are called *electrodes.* The end of the cylinder is covered with a thin sheet of material (the *window*) such as glass, mica, or aluminum to allow radiation to pass through it.* The tube contains a mixture of gasses.

The side of the power supply labeled + is connected to the center wire of the

*Not all Geiger tubes are constructed with a thin end window. In some designs, radiation can enter through other parts of the cylinder.

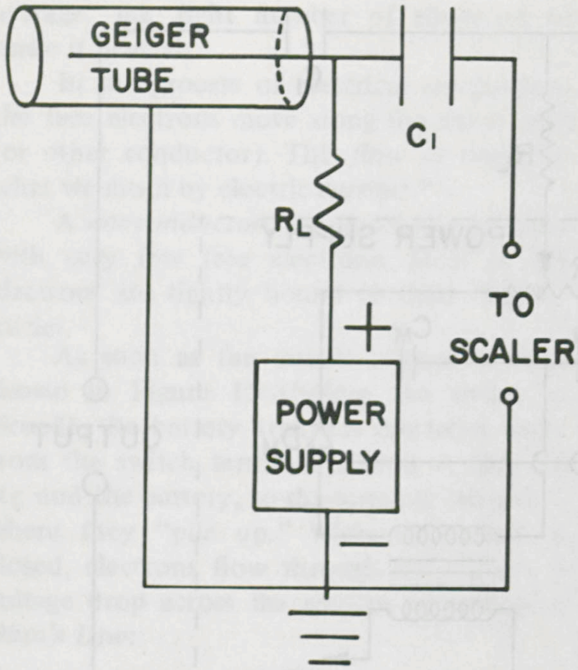

Figure 18. Simplified diagram of a Geiger counter circuit.

Geiger tube by way of R_L. The outer cylinder is connected by a wire to the side of the power supply labeled −. (See Figure 18.)

The power supply of our circuit transfers some electrons from the central wire of the

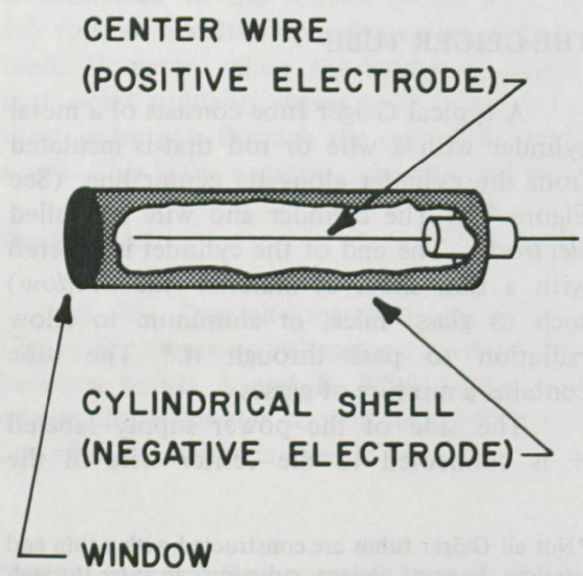

Figure 19. Cutaway view of a Geiger tube.

Geiger tube, through R_L and the power supply, and finally to the inside surface of the cylindrical wall of the tube. This leaves the central wire charged positively and the wall charged negatively. This process takes place very rapidly, and the charge remains on the electrodes until radiation enters the tube. (See Figure 20.)

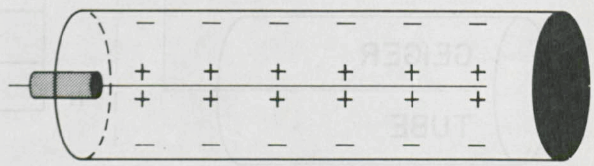

Figure 20. Diagram of Geiger tube, showing charge distribution.

If some of the electrons belonging to the gas atoms inside the Geiger tube could somehow be removed and move through the gas to the central wire, they would neutralize some of the positive charge there and they would then flow around the circuit through R_L and the power supply, back to the cylindrical wall. Radiation entering the Geiger tube makes this possible. In effect, radiation "closes a switch" that permits charge to flow. This happens because the radiation causes *ionization.*

Question 18.

You have observed the relative penetrating abilities of alpha, beta and gamma radiation. Would the window for a Geiger tube designed to count alpha particles be thicker than or thinner than a window for a tube designed to count beta particles?

IONIZATION

Earlier in the module, you studied the nature of matter and some atomic and nuclear properties of atoms. We discussed three types of nuclear radiation. It was pointed out that each of these radiations has the capability of causing *ionization* of atoms.

Since alpha and beta radiations consist of charged particles, ionization takes place as a result of the interaction of their charges with the charges of electrons in the gas atoms of the Geiger tube. Since gamma radiation does not have electric charge, it has fewer interactions with electrons in the gas. However, as the gamma ray passes through the window, which is often made of metal, an electron is sometimes knocked out of the metal. The electron may then enter the Geiger tube and ionize gas atoms.

The atoms from which an electron has been removed is no longer electrically neutral. It has the net charge of one proton. Both the removed electron and the remaining atom are often called *ions* and the combination is called an *ion pair.*

Question 19.

If you were designing a Geiger tube to count gamma rays, what property would you look for in a material for the window?

ION AVALANCHE

The single electron knocked out of an atom would not cause much of a voltage pulse. However, because of the high voltage across the tube, the electron is accelerated toward the center electrode. (See Figure 21.) It moves faster and faster and is soon able to knock an electron out of another atom along the way and thus cause another ionization. The new electron also starts moving rapidly toward the center wire along with the first one and can, in turn, knock still another electron out of an atom. The similarity to a "rock slide" or avalanche is obvious. In this way, the initial electron triggers a build-up of millions of electrons, all heading for the center wire. This large build-up of electrons is called an *ion avalanche.* For each electron, there is a positively charged ion drifting slowly toward the outer shell of the tube and "bumping" other atoms along the way. All of this happens in a small fraction of a second.

When the electrons reach the center wire, they enter it and move through the circuit (R_L and the power supply). Eventually they reach the outer cylindrical surface of the Geiger tube and there they join positive ions (that have moved more slowly through the gas), producing neutral atoms again. The Geiger tube is thus restored to its original condition, ready to repeat the entire series of processes.

This sequence of events in the Geiger tube means that an incoming charged particle triggers an electric current in the circuit, just as the switch did in Experiment C-1b. Thus, once again a pulse is passed through the capacitor to the oscilloscope or scaler.

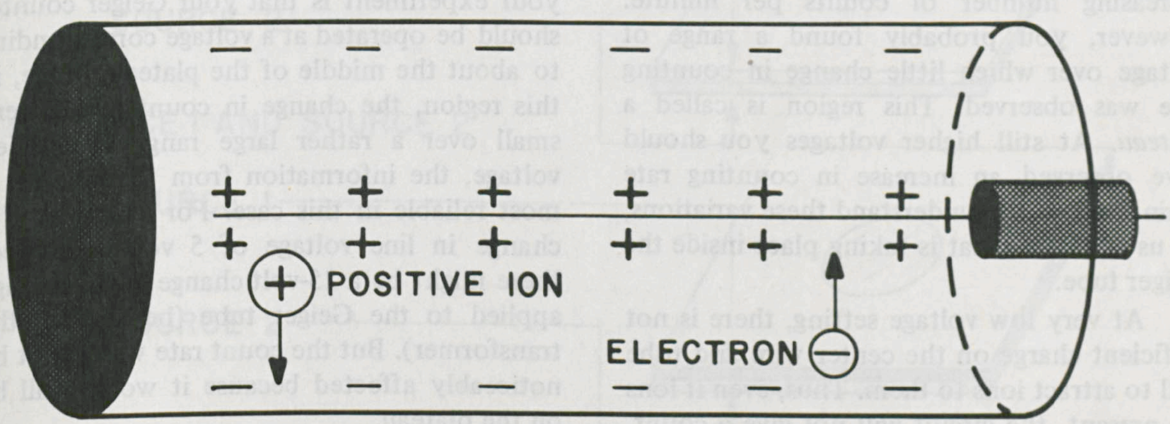

Figure 21. The electron and the positive ion move in opposite directions.

Let us review the processes discussed. The power supply produces a high voltage for the Geiger tube. These two units are connected through a load resistor R_L. When radiation enters the tube and causes ionization, an ion avalanche develops. The resulting current in R_L causes a voltage pulse that is passed on to whatever external component is connected to the Geiger counter (scaler, rate meter, oscilloscope, etc.).

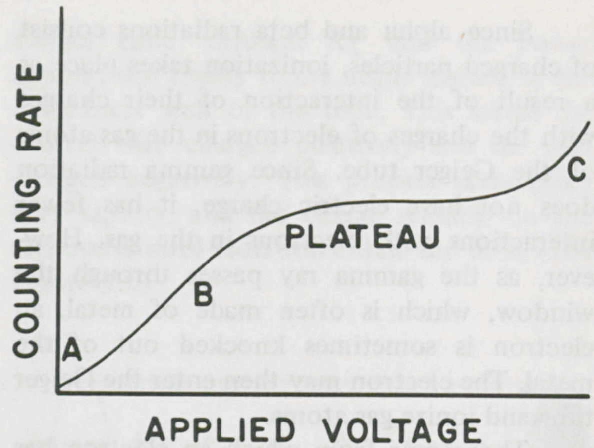

Figure 22. Counting rate versus voltage applied to the Geiger tube.

EXPERIMENT C-2. The Effect of the Applied Voltage on the Counting Rate

First, plug in your Geiger counter and turn the voltage control to its lowest setting. Arrange the controls to take one-minute runs.

Obtain a beta source, such as thallium-204 or strontium-90, and place it close to the window of the Geiger counter. With the voltage control set at its lowest setting, take a one-minute run. When this count ends, raise the voltage by 50 volts and take another one-minute run. Repeat these runs, each time increasing the voltage by 50 volts. At some point beyond 400 volts you will observe an increase in counting rate. Do not take readings beyond that point. Record your data in a table. Plot your data on a graph of counts per minute versus applied voltage. Draw a smooth curve connecting the data points.

Note that the counting rate starts at a very low value for a small value of applied voltage. Increasing the voltage results in an increasing number of counts per minute. However, you probably found a range of voltage over which little change in counting rate was observed. This region is called a *plateau.* At still higher voltages you should have observed an increase in counting rate again. In order to understand these variations, let us consider what is taking place inside the Geiger tube.

At very low voltage setting, there is not sufficient charge on the center wire and tube wall to attract ions to them. Thus, even if ions are present, the circuit will not give a count. This is region A of Figure 22. As the voltage gradually is increased, the charge on the electrodes increases and more and more ions are collected, as in region B. However, not many *secondary ions* are produced. As the voltage is increased further, the secondary ion number increases until an avalanche of ions results. Increasing the voltage further in this region does not produce any greater number of pulses because every particle which enters the Geiger tube is counted. However, increasing the voltage increases the size of the avalanche for each particle, and the pulses become larger. Thus, this gives the region of the curve that we call the plateau. As the voltage is further increased, the counting rate again increases as the conditions for a continuous flow of charges are approached.

The conclusion you may reach from your experiment is that your Geiger counter should be operated at a voltage corresponding to about the middle of the plateau. Since, in this region, the change in count rate is very small over a rather large range in applied voltage, the information from the counter is most reliable in this case. For example, if a change in line voltage of 5 volts occurred, there might be a 25-volt change in the voltage applied to the Geiger tube (because of the transformer). But the count rate would not be noticeably affected because it would still be on the plateau.

Question 20.

Positive ions moving toward the outer shell of the Geiger tube produce very few secondary ions. Why?

Question 21.

Can you guess what would happen to the Geiger tube if you operated it at a voltage higher than that of region C?

EXPERIMENT C-3. Resolving Time of a Geiger Counter

You will again use the thallium-204 sources #1 and #2. Since exact placement of the source is critical for high counting rates, it is important to maintain the same position of a source each time it is used—either alone or in combination with another source. You will make use of a blank source holder. The three cases to be studied are shown in Figure 23. The blank must be identical to a source except for the source material itself.

Carefully mount the Geiger tube in a ring-stand clamp, with the window pointing down directly toward the sources on the base of the stand. Adjust the height of the tube by referring to the results of Experiment A-3. You will need a distance from sources to Geiger tube such that the counting rate for the two sources together is noticeably less than the sum for the two sources taken singly. But the losses shouldn't be over 20%.

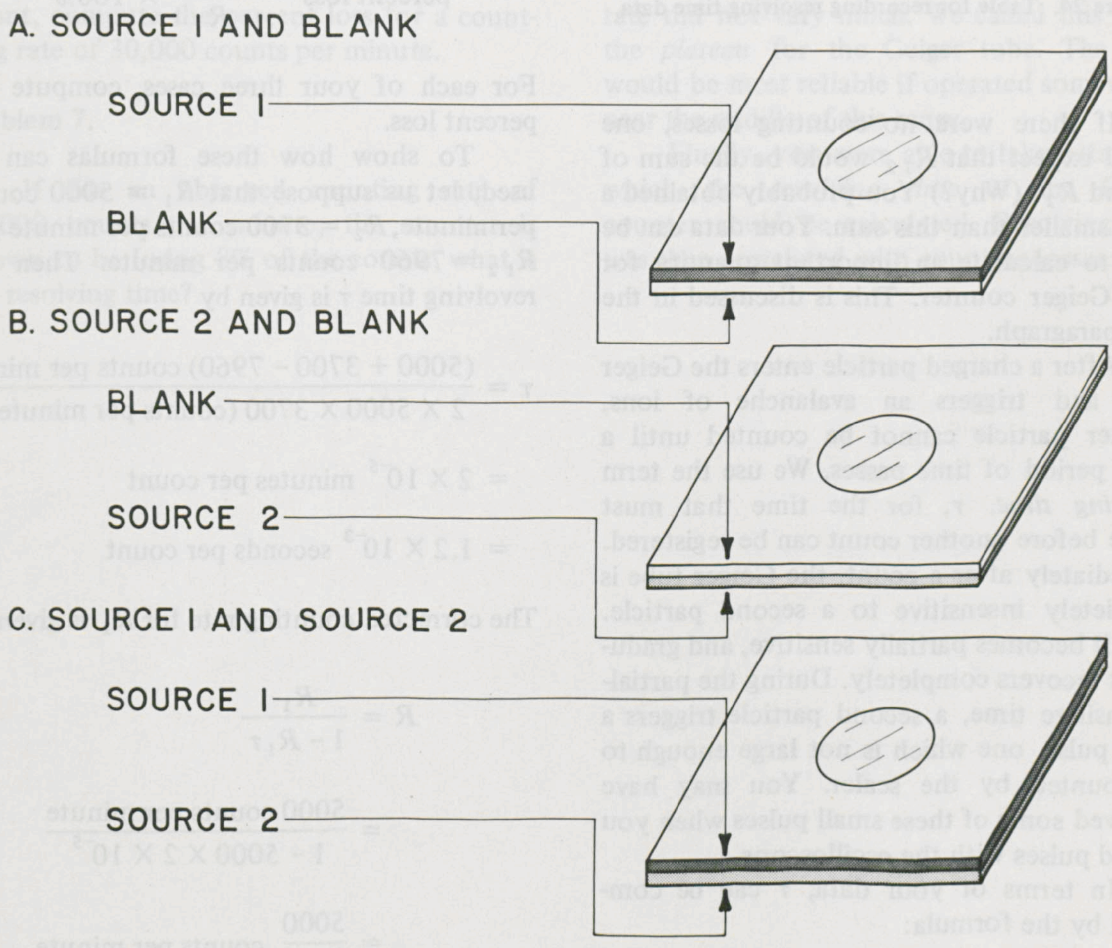

Figure 23. Arrangement of sources.

Take a 5-minute background count. This counting rate must be subtracted from the counting rates observed in the three cases to obtain the net counting rate.

Take 3 one-minute runs and record your data in a table such as that shown in Figure 24.

Source	Net counts per minute
#1 plus blank	R_1 =
#2 plus blank	R_2 =
#1 and #2	R_{12} =

Figure 24. Table for recording resolving time data.

If there were no counting losses, one would expect that R_{12} would be the sum of R_1 and R_2. (Why?) You probably obtained a value smaller than this sum. Your data can be used to calculate an important quantity for your Geiger counter. This is discussed in the next paragraph.

After a charged particle enters the Geiger tube and triggers an avalanche of ions, another particle cannot be counted until a short period of time passes. We use the term *resolving time*, τ, for the time that must elapse before another count can be registered. Immediately after a count, the Geiger tube is completely insensitive to a second particle. Then it becomes partially sensitive, and gradually it recovers completely. During the partially sensitive time, a second particle triggers a small pulse, one which is not large enough to be counted by the scaler. You may have observed some of these small pulses when you viewed pulses with the oscilloscope.

In terms of your data, τ can be computed by the formula:

$$\tau = \frac{R_1 + R_2 - R_{12}}{2 R_1 R_2}$$

This expression was derived using the fact that there are losses in R_1 and R_2 as well as in R_{12}. At the higher rate, the losses are just a greater percentage of the true rate.

Using your data, corrected for background, calculate τ for your Geiger counter.

With the value of τ known, it is possible to make an allowance for counts lost because of the resolving time. The expression for this is

$$R = \frac{R_o}{1 - R_o \tau}$$

where R_o is the observed counting rate and R is the corrected counting rate.

The rate at which counts are *lost* is $(R - R_o)$. The percent loss is

$$\text{percent loss} = \frac{R - R_o}{R} \times 100\%$$

For each of your three cases, compute the percent loss.

To show how these formulas can be used, let us suppose that $R_1 = 5000$ counts per minute, $R_2 = 3700$ counts per minute and $R_{12} = 7960$ counts per minute. Then the revolving time τ is given by

$$\tau = \frac{(5000 + 3700 - 7960) \text{ counts per minute}}{2 \times 5000 \times 3700 \text{ (counts per minute)}^2}$$

$$= 2 \times 10^{-5} \text{ minutes per count}$$

$$= 1.2 \times 10^{-3} \text{ seconds per count}$$

The corrected counting rate for R_1 is given by

$$R = \frac{R_1}{1 - R_1 \tau}$$

$$= \frac{5000 \text{ counts per minute}}{1 - 5000 \times 2 \times 10^{-5}}$$

$$= \frac{5000}{.9} \text{ counts per minute}$$

$$\approx 5560 \text{ counts per minute}$$

The percent loss for R_1 is:

$$\text{percent loss} = \frac{\text{corrected } R_1 - R_1}{\text{corrected } R_1} \times 100\%$$

$$\approx \frac{5560 - 5000}{5560} \times 100\%$$

$$\approx 10\%$$

Use the expression above and the computed value of τ for your Geiger tube to obtain corrected counting rates for your three cases: R_1, R_2, and R_{12}.

Problem 6.

For a resolving time 4×10^{-4} seconds per count, compute the percent loss for a countting rate of 30,000 counts per minute.

Problem 7.

If for an observed counting rate of 30,000 counts per minute, the counter is known to be losing 8% of the counts, what is the resolving time?

SUMMARY

In this section you learned how an incoming radiation particle triggers an *ion avalanche.* The resulting electric current in the Geiger tube gives rise to a voltage *pulse.* This process is possible because the power supply transfers electrons from the center wire of the Geiger tube to the outer shell, leaving the center wire positively charged and the shell negatively charged. Ions produced in the gas are then strongly attracted to these electrodes, producing *secondary ions* along the way.

You learned that pulse size depends on the power supply voltage, but not on the kind of radiation or the energy of the incoming particle.

You were able to find a range of operating voltages over which the counting rate did not vary much. We called this range the *plateau* for the Geiger tube. The tube would be most reliable if operated somewhere near the middle of this range.

Finally, you were able to take data from which the *resolving time* of the Geiger counter could be calculated. Resolving time was then correlated with counting losses.

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